Label-free structural imaging of plant roots and microbes using third-harmonic generation microscopy

Daisong Pan[1†], Jose A. Rivera[1†], Peter Kim[2,3], Max Miao[3], Tomáš Tyml[2,3], Cristina Rodríguez[1], Bing Wang[3], Yasuo Yoshikuni[3], Nathalie H. Elisabeth[2], Trent Northen[3], John P. Vogel[3], Na Ji[1,2,4,]*

[1]Department of Physics, University of California, Berkeley, CA 94720, USA

[2]Biosciences Area, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

[3]U. S. Dept. of Energy Joint Genome Institute, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

[4]Department of Molecular and Cell Biology, University of California, Berkeley, CA 94720, USA

[†]*Equal contribution*

*To whom correspondence should be addressed: jina@berkeley.edu

ABSTACT

Root biology is pivotal in addressing global challenges including sustainable agriculture and climate change. However, roots have been relatively understudied among plant organs, partly due to the difficulties in imaging root structures in their natural environment. Here we used microfabricated ecosystems (EcoFABs) to establish growing environments with optical access and employed nonlinear multimodal microscopy of third-harmonic generation (THG) and three-photon fluorescence (3PF) to achieve label-free, *in situ* imaging of live roots and microbes at high spatiotemporal resolution. THG enabled us to observe key plant root structures including the vasculature, Casparian strips, dividing meristematic cells, and root cap cells, as well as subcellular features including nuclear envelopes, nucleoli, starch granules, and putative stress granules. THG from the cell walls of bacteria and fungi also provides label-free contrast for visualizing these microbes in the root rhizosphere. With simultaneously recorded 3PF fluorescence signal, we demonstrated our ability to investigate root-microbe interactions by achieving single-bacterium tracking and subcellular imaging of fungal spores and hyphae in the rhizosphere.

INTRODUCTION

Root biology research informs wide-ranging areas of intensifying global interest including soil remediation[1], climate[2], genetics[3], and sustainable agriculture[4,5]. Optical microscopy, capable of visualizing plant morphology at sub-cellular resolution, is critical for understanding plant structure and function[5]. However,

compared to more extensively studied plant organs such as stems and flowers, a dearth of imaging studies on plant roots has resulted in roots being continually designated the "hidden half" of the plant body[6].

The native environment of plant roots, composed of soil and organic matters, strongly scatters and absorbs light, severely limiting optical access to plant roots. As an alternative, microfabricated ecosystems such as EcoFABs[7] provide controllable and reproducible growth conditions to plants. The absence of soil in EcoFABs relieves the requirement of uprooting the plant from its growing environment and provides non-destructive optical access for *in situ* imaging of root structure and its immediate microenvironment[8,9].

Single-photon fluorescence microscopy techniques such as confocal microscopy[10] and light sheet microscopy[11–13] have been used to image plant roots[14,15]. However, light scattering by root tissues has limited their applications to relatively transparent or cleared root samples[16]. They also often require the introduction of extrinsic fluorescent labels. Transgenic fluorescent markers are compatible with live root imaging but can only be implemented for plants with established transformation systems and even in the best cases are laborious, whereas vital stains can suffer from poor incorporation[17] or unwanted interference with cellular activity[18]. Thus, a label-free microscopy approach that can image structures at high resolution in opaque live root tissues would be highly desirable but has yet to be demonstrated.

Nonlinear optical microscopy methods utilizing near-infrared excitation light provide greater depth penetration in tissues than single-photon fluorescence techniques, and have been used to image both fluorescently labeled and unlabeled plant tissues[19–23]. Two nonlinear imaging modalities, three-photon fluorescence (3PF) microscopy and third-harmonic generation (THG) microscopy, have recently emerged as a powerful technique to image subcellular resolution at millimeter imaging depths in opaque tissues such as the mouse brain[24,25]. Here, we explored the potentials of using 3PF and THG microscopy for label-free *in situ* imaging at subcellular resolution of live plant roots in EcoFABs, including *Brachypodium distachyon*, a monocot grass known for its genetic tractability and relevance to agricultural crops[26,27], and the dicot *Arabidopsis thaliana*, a central model organism in plant research[28]. We found that THG provided excellent optical resolution and label-free contrast for a variety of subcellular structures, while 3PF from the intrinsic fluorophores of root cells provided complementary structural information. We were able to visualize root hairs, vasculature, as well as subcellular components of mitotically active and border-like cells. In the optically opaque root of *B. distachyon*, THG microscopy imaged vasculature beyond 200 µm in depth in the mature zone and imaged through the entire 230-µm thickness of a root tip. Furthermore, we combined simultaneous label-free and fluorescence imaging to study root-microbe interactions, including real-time monitoring of *Pseudomonas simiae* dynamics in the vicinity of *A. thaliana* roots at single-bacterium resolution and visualizing the fungus *Trichoderma atroviride* adjacent to *B. distachyon* roots at subcellular resolution.

RESULTS

THG microscopy provides label-free contrast for plant root structures at subcellular resolution

THG, a coherent optical process that can convert three near-infrared excitation photons to one visible photon having one-third the excitation wavelength, has its signal originating from the third-order nonlinear susceptibility[29]. Under tight focusing conditions in microscopy, its contrast derives from the local optical heterogeneities within the excitation focus[19,30–32]. When the absorption of three near-infrared photons also promotes a fluorophore to its excited electronic state, 3PF can be generated by the same excitation laser. At longer wavelengths than the third-harmonic signal, 3PF signal can be spectrally separated from and simultaneously detected with the THG signal. The third-order nonlinear excitation involved in THG and 3PF confines the signal generation to within the excitation focus, thus optically sections 3D samples.

We conducted all imaging experiments using a custom-built multimodal microscope[25] capable of simultaneously acquiring THG and 3PF signals (**Fig. 1a**). A near-infrared excitation laser beam (λ = 1300 nm; Monaco-Opera-F system, Coherent Inc.) propagated through a laser-scanning assembly comprising galvanometric mirrors (X,Y) and scan lenses to overfill a high-numerical-aperture (NA) water-dipping objective (Olympus XLPLN25XWMP2, NA 1.05, 25×). THG at 433 nm and 3PF (500 – 550 nm) signals were separated from the excitation light by a dichroic mirror (Dm) and further separated into two paths by an additional dichroic mirror for detection by photomultiplier tubes. We measured the point spread function (PSF) of our microscope by 3PF imaging of 0.2-µm-diameter fluorescent beads. The PSF had a lateral full width at half maximum (FWHM) of 0.65 µm in the xy plane and an axial FWHM of 1.78 µm (insets, **Fig. 1a**).

Seedlings of *B. distachyon* or *A. thaliana* were allowed to germinate within an EcoFAB growth chamber[9] made of coverglass and PDMS before loading into the microscope (Methods). The excitation light entered through the coverglass side of the chamber and the emitted THG and 3PF signals were collected and detected in the epi direction. When the excitation focus was entirely within the coverglass or the growth medium, there was no THG signal generated due to the optical uniformity of the material within the focus[29,30]. When the excitation focus bisected the coverglass-medium interface, a strong THG signal was generated due to the abrupt change of susceptibility from glass to growth medium (**Fig. 1b**).

When the excitation focus was scanned across *B. distachyon* roots, THG signal provided high-resolution label-free visualization of various structures in both axial (**Fig. 1c**) and lateral (**Figs. 1d-f**) planes. Within the root, plant cells appeared as individual compartments with strong THG signal observed at their cell walls, likely due to the different optical properties of the cell wall and the cytopolasm[33,34]. In an example axial (xz) image (**Fig. 1c**), we observed elongated cells with root hairs protruding from the root surface – a well-known characteristic of the mature root zone[35]. Here from left to right, cells progressively diminished in size, corresponding to the transition

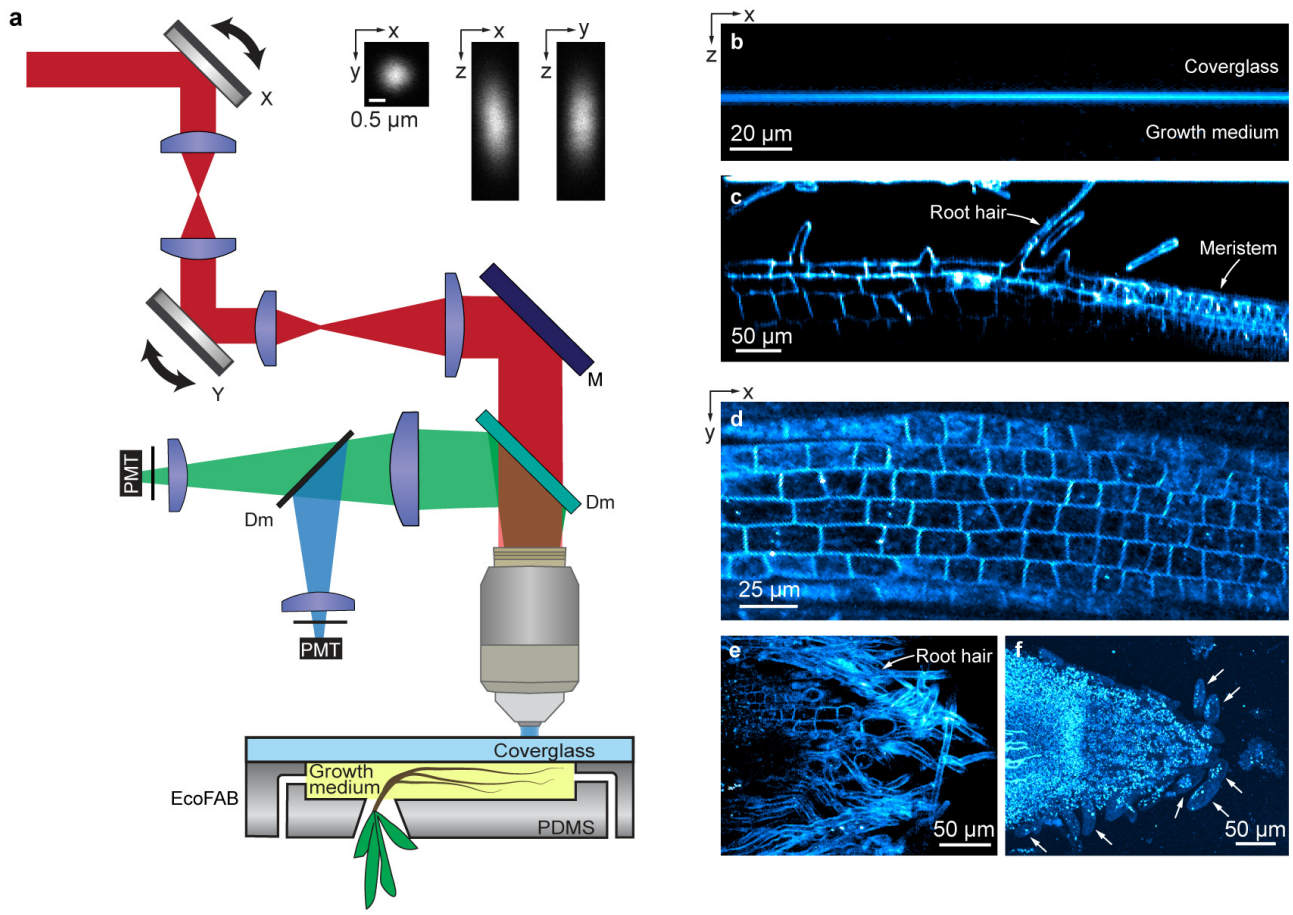

Figure 1: THG microscopy reveals plant root structure at subcellular resolution. (**a**) Schematics of the microscope and EcoFAB. Red: excitation light; Green: 3P fluorescence; blue: THG. X, Y: X and Y galvanometer mirrors; M: mirror; Dm: dichroic mirror; PMT: photomultiplier tube. Insets: lateral (xy) and axial (xz, yz) images of a 0.2-µm-diameter bead. (**b**) xz THG image of the interface between coverglass and growth medium. (**c**) xz and (**d,e**) xy THG images of *B. distachyon* roots inside the EcoFAB chamber. (b,c) acquired at 2 µm/pixel in X and 1 µm/pixel in Z. (d,e) acquired at 1 µm/pixel. (**f**) Brightest-spot projection with depth cueing (100% to 50%) of an 88-µm-thick image stack of a root tip acquired at 0.8 µm/pixel and z step size of 2.75 µm. White arrows: border-like cells. Post-objective power: (**b**) 2 mW, (**c,d**) 3 mW, (**e**) 4 mW. (**f**) 2.4-2.8 mW.

into the meristematic zone. A similar transition was observed in a lateral (xy) image (**Fig. 1d**). Another lateral image section of a slightly inclined root revealed root hairs enveloping the root's surface (**Fig. 1e**). Imaging the tip of a root, we observed cells that were detached from the primary body of the root near the root cap region (white arrows, **Fig. 1f**), reminiscent of border-like cells[36,37] and suggesting that roots grown in the EcoFAB system resemble roots grown in soil. These label-free high-resolution images motivated us to systematically explore the cellular and subcellular features revealed by THG in *B. distachyon* roots, as detailed below.

THG and 3P autofluorescence microscopy imaging of the mature zone of *B. distachyon* roots

In addition to THG, intrinsic contrast can arise from the autofluorescence of endogenous chromophores in biological specimens. Spectrally separating the THG and 3P autofluorescence signals, we simultaneously acquired THG and 3P autofluorescence images in the mature zone of *B. distachyon* roots (**Fig. 2; Supplementary Video 1**).

Roots in the mature zone contain concentric layers of epidermis, cortex, endodermis, and vasculature. In epidermis and cortex, THG and 3P autofluorescence signals co-localized at cell walls (**Fig. 2a-c**). Even though THG signal was ~3.4–8.8× stronger than 3P autofluorescence signal, cell walls were easily visible in both channels. The

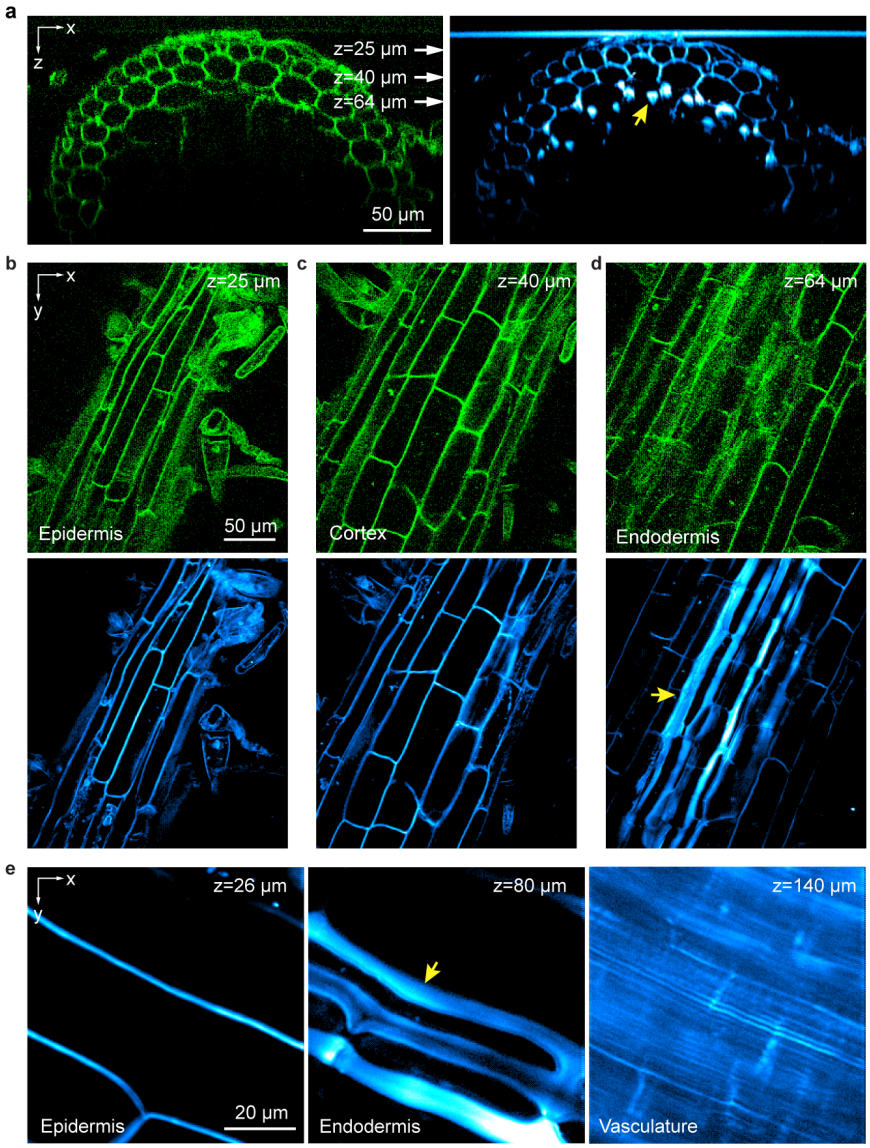

Figure 2: 3P autofluorescence and THG microscopy visualize epidermis, cortex, endodermis, and vasculature in the mature root zone of *B. distachyon* roots. (**a**) 3P autofluorescence (green) and THG (cyan) xz images acquired at 1 µm/pixel showing a cross section of mature root zone. (**b-d**) xy images acquired at depths indicated by white arrows in **a** corresponding to putative (**b**) epidermis, (**c**) cortex and (**d**) endodermis tissues. Pixel size: 1 µm/pixel. (**e**) xy THG images of root tissues at 26 µm, 80 µm, and 140 µm depths, corresponding to putative epidermis, endodermis and vasculature, respectively. Pixel size: 0.3 µm/pixel. Post-objective powers: (**a-d**) 2.6 mW, (**e**) 1.2, 1.6, and 14 mW from left to right.

contrasting composition of the plant cell wall and the surrounding cytoplasm generated THG signal, while the phenolic compounds in the cell wall[38–40] were likely the source of autofluorescence.

Right before the THG and autofluorescence signals dropped off at larger depths, in the THG images we observed striation features of greater brightness and larger widths than the cell walls above (yellow arrows, **Fig. 2a,d,e**). Interestingly, the corresponding autofluorescence image did not exhibit this large increase of brightness (e.g., 65 – 83 µm, **Supplementary Video 1**), suggesting that THG signal was caused by a substantial change in the optical susceptibility. The location and morphology of these bright striated features of ~10 µm width were consistent with Casparian strips in endodermis, which surround the vascular cylinder and regulate the passage of water and other solutes between cortex and vasculature[35]. The distinct molecular composition[41] and thickness of Casparian strips from those of regular cell walls presumably led to its stronger THG contrast. Below the endodermis, vasculature structures were visualized as parallel channels ~1.5 µm apart (**Fig. 2e**). Although ~10× higher excitation power was needed for vasculature than for cells in epidermis and Casparian strips in endodermis, we were able to observe structures more than 200 µm deep into the mature root (**Supplementary Video 1**).

THG and 3P autofluorescence microscopy image meristem and root tip of of *B. distachyon* roots at subcellular resolution

Compared with differentiated cells in the mature zone, cells in the meristem region contain more intracellular features required for root growth, which were visualized in the intracellular space in both 3P autofluorescence and THG cross-sectional images of a *B. distachyon* root (**Fig. 3a**). As in the mature zone, cell walls generated stronger THG signal than 3P autofluorescence signal and strong THG signal was observed in band-like structures presumed to be Casparian strips (white arrow, **Fig. 3a**).

In contrast to cells in the mature zone, cells in the meristem region were less elongated and approximately isodiametric (**Fig. 3b-e**). In 3P autofluorescence images, we observed ellipsoidal structures occupying most of the cell volume (**Fig. 3b,d**). We speculated that they were enlarged nucleus, a characteristic feature of meristem cells, with their autofluorescence arising from the aromatic chemical structures of nucleic acid molecules themselves[42]. In several nuclei, we found bright and micron-sized autofluorescent aggregates (yellow arrows, **Fig. 3b,d**) that were likely nucleoli, whose higher molecular density[43] could lead to the brighter fluorescence observed.

Due to the coherent nature and symmetry requirements of THG, subcellular structures exhibited distinct features in THG images (**Fig. 3c,d**) from those of 3P autofluorescence. When the excitation focus was within the optically uniform portion of the cell (e.g., cytoplasm or the non-nucleolus, nucleoplasm part of nucleus)[44], THG signal was minimal. The varying susceptibilities across cytoplasm and nucleoplasm, however, gave rise to strong THG signal at the nuclear envelope (**Fig. 3e**). Inside the nuclei, strong THG signal was observed from the putative nucleoli (yellow arrows, **Fig. 3c,e**) due to their distinct optical susceptibility from nucleoplasm[44]. In both

138 autofluorescence and THG images, nucleoli were often found near the nuclear envelopes, consistent with previous
139 reports for plant cells[45,46].

140 The distinctive features of meristem cell nuclei and the strong signal of cell walls in THG images provided
141 us a label-free method to monitor cell division. For example, we observed a dividing cell with two daughter nuclei
142 close to being separated (dashed box, **Fig. 3d,e**). In the equatorial plane[47], a nascent cell wall could be detected in
143 the THG image (red arrow, **Fig. 3e**).

144 THG also provided label-free structural contrast at subcellular resolution at the root tip encompassing the
145 apical meristem and the root cap (**Fig. 4**). Imaging through a 230-µm-thick root tip (**Supplementary Video 2**), THG
146 revealed a clear boundary between the meristem and the root cap[35] (white arrows in **Fig. 4a**, a projected image

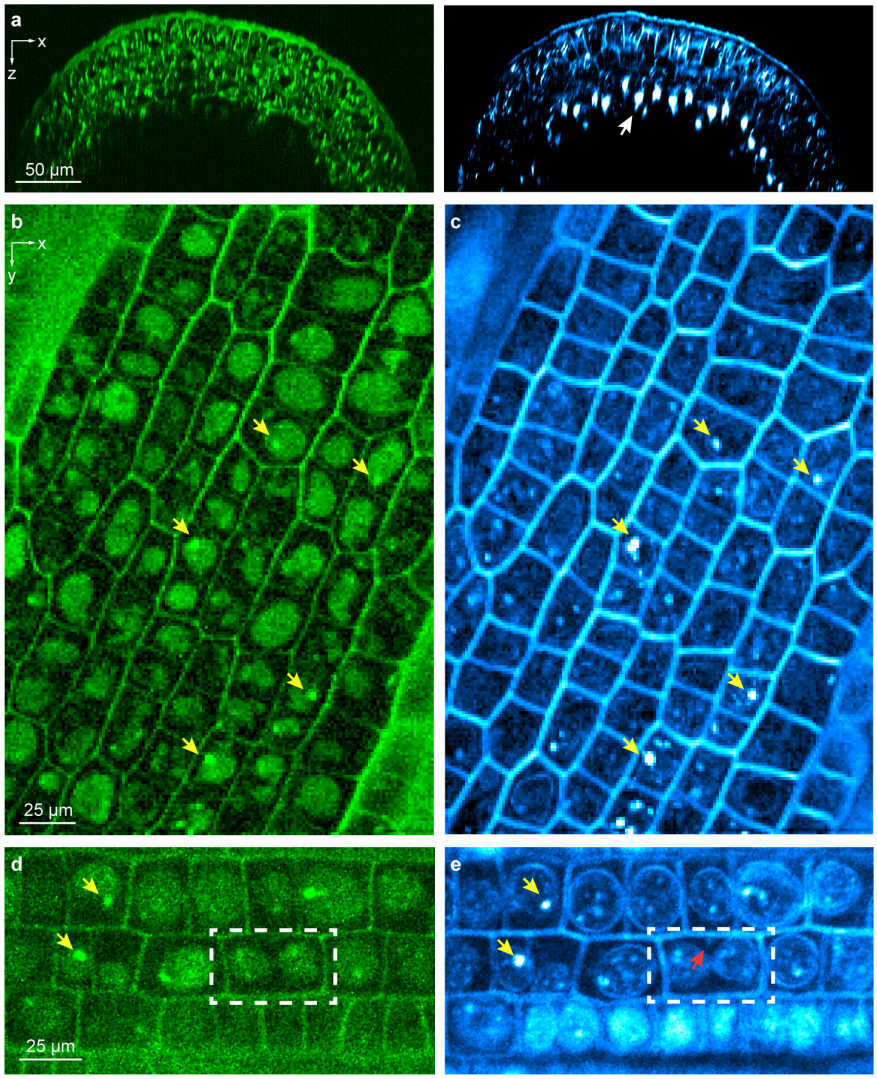

Figure 3: 3P autofluorescence and THG microscopy provide label-free imaging of the *B. distachyon* root meristem at subcellular resolution. (**a**) 3P autofluorescence (green) and THG (cyan) xz images acquired at 0.3 µm/pixel showing a cross section of the root meristem. White arrow: putative Casparian strip. (**b-e**) 3P autofluorescence (green) and THG (cyan) xy images acquired at (**b,c**) 0.5 µm/pixel and (**d,e**) 0.3 µm/pixel. Yellow arrows: putative nucleoli; Dashed white box: a mitotic cell; red arrow: nascent cell wall. Post-objective power: (**a**) 5.3 mW; (**b,c**) 5 mW; (**d,e**) 7 mW.

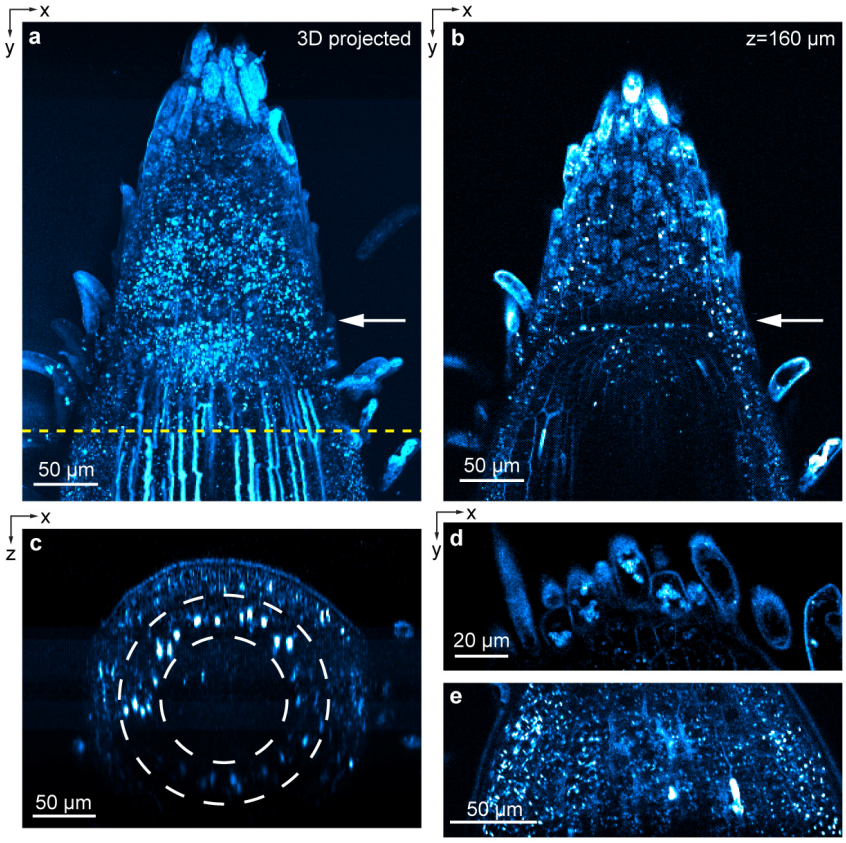

Figure 4: THG imaging of *B. distachyon* apical meristem and root cap. (**a**) Brightest-spot projection with depth cueing (100% to 50%) of an image stack through a root tip. 230-µm-thick image stack acquired at 1 µm/pixel and z step size of 2 µm. (**b**) xy image acquired at z=160 µm. White arrows in **a,b**: boundary between meristem and root cap. (**c**) xz images acquired along dashed yellow line in **a**. (**d,e**) xy images from two other root samples acquired at 0.5 µm/pixel. These roots were placed in between a microscope slide and a coverslip instead of inside EcoFAB to minimize sample motion. Post-objective power: (**a-c**) 3-15 mW; (**d**) 4mW; (**e**) 3.4 mW.

of a 373 × 310 × 230 µm^3 volume, and **Fig. 4b**, a single image section). Putative Casparian strips were found within the THG images of the meristem region but not the root cap region (**Fig. 4a**; **Supplementary Video 2**), consistent with known anatomy[35]. An axial cross-sectional view of the apical meristem region showed a complete encirclement of the central vasculature by the Casparian strip (**Fig. 4c**). Because light scattering and sample-induced aberration degraded focal intensity at deep depths, the Casparian strips in the bottom half of the root were substantially dimmer than those above. In cells protruding from the tip of the root cap, we observed bright granules of 3-7 µm in size (**Fig. 4d**), whose location and morphology were consistent with starch granules[48]. Throughout the apical meristem and root cap, we also saw smaller granules of 1-3 µm in size (**Fig. 4e**). We speculated that they may be processing bodies or stress granules[49].

THG and 3PF microscopy enable simultaneous imaging of plant roots and microbes in the rhizosphere

In addition to imaging plant roots themselves, the ability to simultaneously image microbes in the rhizosphere, the region in the vicinity of the roots where the microbiome interacts with the plant, would help

159 understand the complex mechanisms through which root-microbe interactions impact plant growth[50,51]. We found
160 that THG can be combined with 3P fluorescence to simultaneously image plant roots and bacteria as well as fungi
161 in the rhizosphere *in situ*.

162 We first imaged two strains of *Pseudomonas simiae* bacteria[52] near the surface of an *A. thaliana* root,
163 including a GFP-labeled wildtype strain and a mutant strain without fluorescent labeling. Both *P. simiae* strains
164 appeared as rod-like structures in THG images, often forming aggregates around the root tissue (**Supplementary**
165 **Videos 3,4**; right panel, **Fig. 5a**). The GFP-labeled wildtype *P.simiae* had much stronger 3P fluorescence signal than
166 the autofluorescence from root tissue (left panel, **Fig. 5a**) and showed up in both 3PF and THG channels at
167 comparable signal strengths. During time-lapse imaging over 160 s at 1.1 Hz frame rate (**Supplementary Video 4**,
168 **Fig. 5b**), we observed stationary (red and purple arrowheads), slowly moving (yellow arrowheads), as well as fast
169 moving (orange arrowheads) bacteria near the *A. thaliana* root. These results indicate that our microscope is
170 capable of simultaneously imaging and tracking of bacteria in the root rhizosphere, and that with additional
171 fluorescence labeling for 3PF, it can image multiple bacterial strains simultaneously.

172 We also investigated fungal colonization by imaging *B. distachyon* roots inoculated with *Trichoderma*
173 *atroviride* strain IMI[53,54], which had its nuclei labeled with GFP (H1-GFP[55]). Filamentous structures consistent with
174 fungal hyphae were observed near root hairs in THG images, with their signal likely coming from fungal cell walls
175 (**Fig. 5c**). Embedded within these putative hyphal structures were multiple green-fluorescent punctates of 1.5-2.5
176 µm in size (white arrowheads and inset, **Fig. 5c**), in line with the expected sizes of *T. atroviride* nuclei[56]. In another
177 sample, we also found punctate structures in THG images that were not labeled with GFP (pink arrowheads, **Fig.**
178 **5d**). In addition, spherical features with high THG signal were observed in close proximity to root hairs (white
179 arrows, **Fig. 5d**). These spheres were 4-6 µm in diameter and were consistent with being fungal spores, with
180 several of them having colocalized, GFP-labeled nuclei (inset, **Fig. 5d**). Therefore, THG microscopy proved to be a
181 valuable tool for visualizing fungal hyphal structures, spores, and nuclei, alongside root structures. When
182 combined with fluorescent labeling, the simultaneous detection of 3PF and THG signals can provide more specific
183 structural insights into the interactions between roots and fungi.

184 **DISCUSSION**

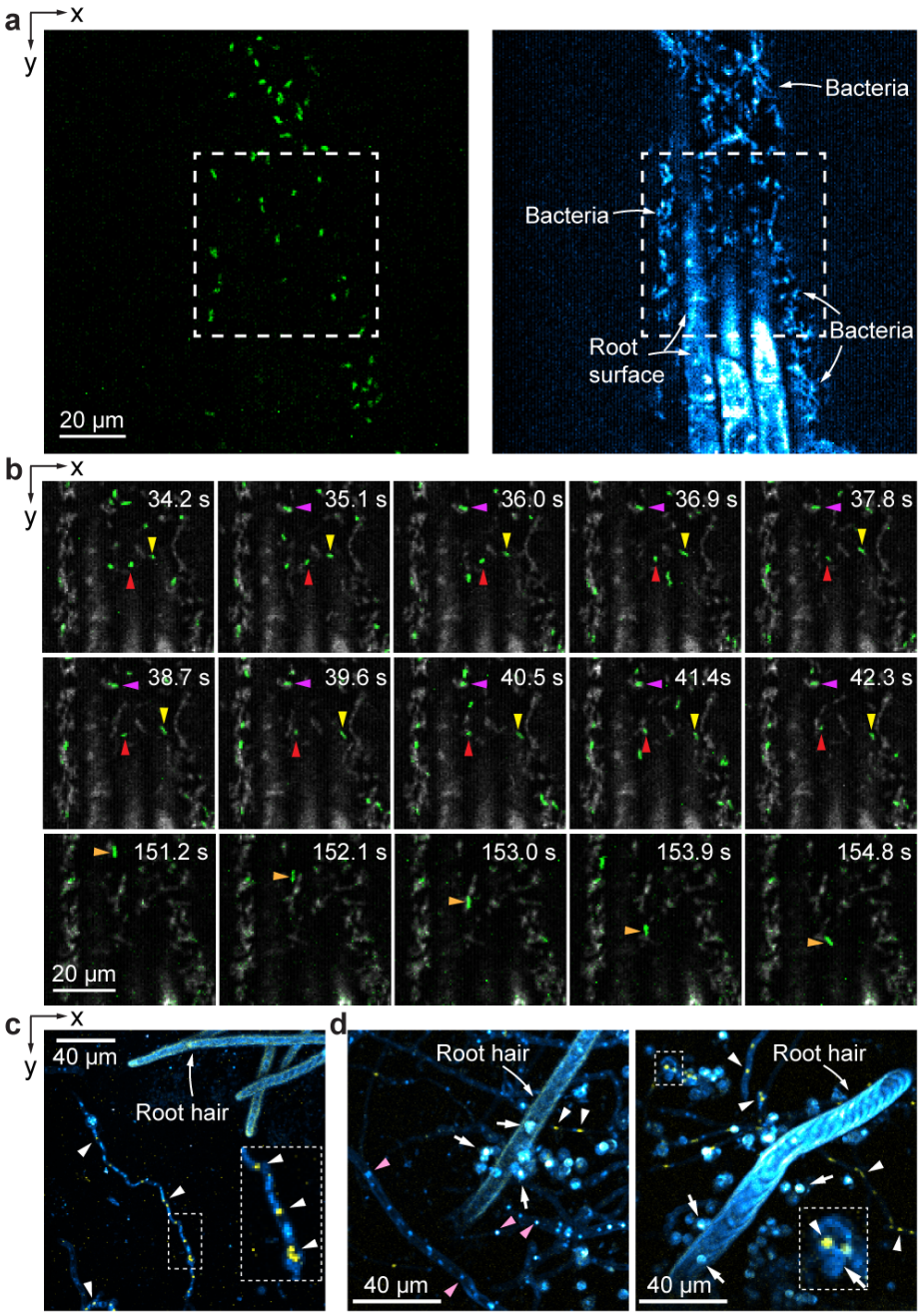

Figure 5: Imaging root-microbe interactions at high spatial and temporal resolution. (**a**) 3PF (green) and THG (cyan) xy images of *A. thaliana* root inoculated with two strains of *P. simiae* (wildtype *P. simiae* labeled with GFP, mutant *P. simiae* without GFP). (**b**) Consecutive frames of time-lapse imaging of the dashed box area in **a** with 3PF in green and THG in gray. Red/purple, yellow, and orange arrowheads: stationary, slowly-moving, fast-moving bacteria, respectively. (**c,d**) Maximal intensity projected 3PF (yellow) and THG (cyan) images of *B. distachyon* roots inoculated with *T. atroviride* strain IMI with GFP-labeled nuclei. (**c**) 50-µm-thick image stack acquired at 0.75 µm/pixel and z step size of 2.5 µm. (**d**) 70-µm-thick image stacks acquired at 0.5 µm/pixel and z step size of 2.5 µm. White arrowheads: GFP-labeled nuclei; pink arrowheads: unlabeled nuclei; white arrows: spores. Insets: zoomed-in views of white dashed boxes. Post-objective power: (**a, b**) 3.4 mW; (**c**) 5.6mW; (**d**) 5.3 mW.

185 THG microscopy combined with microfabricated ecosystems allowed us to capture subcellular-resolution
186 images of living plant roots without extrinsic fluorescent labels. Because THG signal originates from heterogeneity

of optical susceptibilities within the excitation focal volume, it generates label-free visualization of cell walls. The 1.3-µm excitation light penetrated deep into the opaque tissues of *B. distachyon* roots, which are ~2.5× thicker[57] than the more widely studied and optically transparent roots of *A. thaliana*, and enabled us to visualize the vasculature in mature roots and image through the entirety of a 230-µm-thick root tip. Given that all cells in plant roots possess cell walls generating strong THG signal, THG microscopy can provide organ-scale views of root structures at subcellular resolution. In contrast to electron microscopy, which also offer a view of subcellular features, THG microscopy can be applied to live roots without labeling. Furthermore, due to its distinct wavelength, THG signal can be combined with simultaneously acquired fluorescent signals, either from the autofluorescence of endogenous molecules or from exogenous fluorescent labels, to provide structural context for biological processes of interest.

The structural features we observed in THG images are consistent with the known anatomy of plant roots. These include root hairs and elongated cells in the mature root zone. In both mature and meristem roots, we observed the layered arrangement of epidermis, cortex, and endodermis. Within endodermis, we found longitudinal striation features with strong THG signal that terminated at the root cap and were consistent with the location and morphology of Casparian strips. In the root meristem, THG contrast allowed us to visualize nucleoli and nuclear envelopes, providing information on stages of cell division. These structural identifications were strengthened by simultaneously recorded 3P autofluorescence signals from cell walls, nuclei, and nucleoli. In both apical meristem and root cap, between which a clear boundary can be identified in their THG images, the subcellular resolution of our imaging system allowed us to visualize and differentiate granules of varying sizes. Whereas starch granules were observed in root cap cells and border-like cells, we speculated that the small and bright punctates throughout meristem and root cap were likely stress-related granules, whose identities need to be further confirmed with molecular labeling approaches.

In addition to providing global structural information throughout the plant roots at subcellular resolution, THG microscopy also allows one to image bacteria and fungi in the rhizosphere. Because both bacteria and fungi have cell walls, they could also be visualized in a label-free manner by THG microscopy. Transgenic bacteria and fungi with fluorescent protein labels further improve the specificity of structural imaging. With multimodal THG and 3P fluorescence imaging, we were able to observe dynamics of bacterial distribution and fungal spores and hyphae near roots *in situ*. With deep penetration depth and optical sectioning capability, THG and 3P fluorescence microscopy therefore enable the investigation of root-microbe interactions throughout rhizosphere and within plant roots at high spatial and temporal resolution.

It should be noted, however, that plant cells are susceptible to light- and/or heat-induced damages, especially during multiphoton excitation[58,59]. In our experiment, extended imaging of meristem zone at post-objective powers over 10 mW always induced damage in the form of increasing the amount of bright punctates.

220 Mature zone, on the other hand, withstood prolonged imaging at tens of mW without exhibiting visible damage.
221 Care should always be taken to ensure that the biological process of interest is not unduly perturbed by imaging.

222 Our combined EcoFAB and multimodal imaging approach provides a powerful tool for studying the cellular
223 structure of the roots. The large imaging depth of THG and 3P fluorescence microscopy enables the study of root-
224 penetrating bacteria in opaque root tissues[60]. THG microscopy's ability to visualize dividing root cells will enable
225 studies on cellular division, elongation, and differentiation during root growth. Growth conditions could be altered
226 within the EcoFAB chamber – providing a testbed for investigating how roots respond to environmental conditions,
227 such as salinity or nutrient levels[61], at high spatiotemporal resolution. In summary, by integrating microfabricated
228 systems with nonlinear optical microscopy for label-free imaging of plant roots, we expect that our approach will
229 illuminate the "hidden half" of the plant, shedding light on numerous unexplored facets of root biology.

230 **METHODS**

231 **3PF and THG microscopy setup**

232 A simplified diagram of our multimodal (3PF and THG) microscopy is shown in **Fig. 1a**. The excitation source (not
233 shown) consisted of an optical parametric amplifier (Opera-F, Coherent) pumped by a 40-W femtosecond laser
234 (Monaco 1035-40-40, Coherent). Opera-F was tuned to generate 1,300 nm output at 1 MHz. A Pockels cell (M360-
235 40, Conoptics) controlled the light power. A homebuilt single-prism compressor[62] was used to cancel out the group
236 delay dispersion (GDD) of the excitation beam path. The excitation laser beam was reflected by two conjugated
237 galvanometric scanning mirrors (6215H, Cambridge Technology) and relayed to the back-pupil plane of a high NA
238 water-dipping objective (Olympus XLPLN25XWMP2, NA 1.05, 25×) by two pairs of scan lenses (SL50-3P and SL50-
239 3P, SL50-3P and TTL200MP; Thorlabs). The objective was mounted on a piezoelectric stage (P-725.4CD PIFOC,
240 Physik Instrumente) for axial translation of the excitation focus. The fluorescence and THG signals were collected
241 by the same objective, reflected by a dichroic mirror (FF665-Di02-25x36, Semrock) and detected by two
242 photomultiplier tubes (H10770PA-40, Hamamatsu). An additional dichroic mirror (Dm, FF458-Di02-25x36,
243 Semrock) and two filters (FF03-525/50-25 for fluorescence, FF01-433/24-25 for THG; Semrock) were used to split
244 and filter the 3PF and THG signals. Frame rates were 0.2 – 0.6 Hz except for **Fig. 4**, which was acquired at 0.03 –
245 0.08 Hz, and **Fig. 5a,b**, which was acquired at 1.1 Hz.

246 **Bead sample**

247 Carboxylate-modified fluorescent microspheres (FluoSpheres™, Invitrogen) were immobilized on poly(l-lysine)-
248 coated microscope slides (12-550-12, Fisher Scientific).

249 **Imaging EcoFAB fabrication**

250 Imaging EcoFAB devices were fabricated as described previously[9]. Negative molds for imaging EcoFAB were 3D
251 printed using a Form2 printer (Formlabs) with clear resin version 4 (Formlabs). EcoFAB design can be obtained
252 from https://eco-fab.org/device-design/. Each EcoFAB device was housed in a magenta box with a vented lid (MK5,
253 with vented lid, Caisson Labs) for autoclave sterilization.

254 ***Brachypodium distachyon* growth conditions**

255 *Brachypodium distachyon* line Bd21-3 seeds was used for this study[63]. Seeds were dehusked and surface sterilized
256 in 70% ethanol for 30 s, followed by 50% v:v bleach (with 6.25% sodium hypochlorite chlorine) for 5 min, and
257 rinsed 5 times with sterile milliQ water[9]. Seeds were then arranged on a sterile petri dish containing ½ Murashige
258 and Skoog basal salt media (Caisson Labs) with 1% phytogel (Sigma-Aldrich). Surface sterilized seeds were
259 stratified in the dark at 4 °C for 3 days. Following stratification, seeds were allowed to germinate in a growth
260 chamber at 25 °C at 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 16-hr light/8-hr dark. Three Days post germination, seedlings were
261 transplanted into sterilized imaging EcoFABs containing 0.5× MS media with 0.8% phytogel[9]. Following
262 transplantation, plants were grown in the growth chamber for three more days before imaging. All root samples
263 were imaged within the EcoFABs except for **Fig. 4**, for which the plant was taken out of the EcoFAB and imaged
264 with its root between two glass coverslips to reduce root tip motion.

265 **Trichoderma culture conditions and Inoculation**

266 Three days post germination, sterile *Brachypodium distachyon* seedlings were inoculated with *Trichoderma*
267 *atroviride* strain IMI[54] containing nuclear GFP label (H1-GFP) (generously provided by Drs. Catherine Adams and
268 Louis Glass, University of California Berkeley, CA, USA). Fungal spores were grown on PDA plates at 28 °C for 7
269 days 12/12 night/day cycle to induce sporulation. Spores were then harvested using sterile distilled water and
270 separated from mycelia using a 0.4 micron filter (Pall). Spore concentration was determined using Neubauer
271 chamber and then diluted to a spore suspension of $1x10^6$ spores/ml. Seedlings were soaked in the spore
272 suspension for 2 hours prior to transplanting onto Imaging EcoFABs[64]. Following transplantation, plants continued
273 growing in the growth chamber for two more days before imaging.

274 ***Arabidopsis thaliana* and *P. simiae* sample preparation**

275 Seeds of *Arabidopsis thaliana* Col-0 (stock # CS66818) were obtained from the Arabidopsis Biological Resource
276 Center (Ohio State University, Columbus, OH). Seeds were surface-sterilized by immersion in 70% (v/v) ethanol
277 for 2 min, followed by immersion in 10% (v/v) household bleach containing 0.1% Triton X-100 (Roche Diagnostics
278 GmbH) were stratified in distilled water at 4°C for 2 days. In this study, we utilized two strains of the root-
279 colonizing bacterium *Pseudomonas simiae*, the non-fluorescently labeled strain *P. simiae* WCS417r and the eGFP-
280 expressing strain *P. simiae* SB642, which has been previously characterized[52]. Both strains were pre-cultured under

281 kanamycin selection (150 µg·ml^{-1}) in Luria-Bertani medium (Sigma-Aldrich) diluted in 0.5× MS medium containing
282 2.15 g/L, 0.25 g/L of MES monohydrate (ChemCruz), and buffered to pH 5.7. The pre-cultured bacterial cells were
283 washed twice with 0.5× MS medium and used to inoculate the stratified seeds of *A. thaliana* at an initial OD600
284 of 0.01 for each strain. The inoculated seeds were sown into agar-filled imaging EcoFAB chamber. The growth
285 medium contained 0.5× Murashige and Skoog basal salt mixture (Sigma-Aldrich), 2.5 mM of MES monohydrate
286 (ChemCruz), and was buffered to pH 5.7 and solidified with 1 wt% SFR agarose (Electron Microscopy Sciences).
287 *Arabidopsis* seedlings were grown under 16 h light (140 µmol·m^{-2}·s^{-1}) and 8 h dark regime at 23 °C for 10-14 days.

288 **Digital image processing**

289 Imaging data were processed with Fiji[65]. We used the 'Green' lookup table for 3PF images and the 'Cyan hot'
290 lookup table for THG images. In **Fig. 5b**, the 3PF and THG signals were presented with 'Green' and 'Gray' lookup
291 tables, respectively. For **Fig. 5c,d**, the 3PF and THG signals were presented with 'Yellow' and 'Cyan hot' lookup
292 tables, respectively. To improve visibility, saturation and gamma of some images were adjusted. For **Fig. 5d**, we
293 applied the 'RemoveOutliers' function in Fiji to eliminate hot pixels. We generated three-dimensional projection
294 images (**Fig. 1f** and **Fig. 4a**) and a video (the second half of **Supplementary Video 2**) using Fiji's '3D Project' function
295 with 'brightest-point projection' and depth cueing set at 100% to 50%.

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301 **Author contribution.** T.N., J.V., and N.J. conceived of the project; J.A.R. designed and built the microscope with
302 help from C.R.; P.K. and M.M. prepared *B. distachyon* samples; D.P., J.A.R., P.K., and M.M. acquired *B. distachyon*
303 images; M.M. prepared *B. distachyon* and *T. atroviride* samples; D.P. and M.M. acquired *B. distachyon* and *T.*
304 *atroviride* images; T.T. and N.H.E. prepared *A. thaliana and P. simiae* samples; D.P. and T.T. acquired *A. thaliana*
305 *and P. simiae* images; D.P., J.A.R. and N.J. wrote the manuscript with inputs from all authors.

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