EGUSPHERE-2025-3044 | Short communication

Mapping the fertosphere's phosphorus availability distribution in a field trial using a novel diffusive gradients in thin-films (fDGT) technique

Casey Louise Doolette, Euan Smith, Ehsan Tavakkoli, Lukas van Zwieten, Brigid Ann McKenna, Peter Martin Kopittke, and Enzo Lombi

Handling editor: Rafael Clemente, rclemente@cebas.csic.es

Yellow – Reviewer's comments

Green – Authors's responses

Underlined text – new text to add to the manuscript

RC1: A very interesting abstract. No additional comments.

We thank the anonymous reviewer for reviewing this manuscript and their support of this work.

RC2:

1. This is a high-quality manuscript presenting a significant methodological advance with clear relevance to improving phosphorus (P) use efficiency in agriculture using a new methodological approach which is building on an established technique to analise available fractions of P (DGT). The work is robust, novel, and well-structured. The core achievement is the successful development and first field application of a novel, gel-free "fDGT" device for the two-dimensional, *in-situ* mapping of labile P availability around fertilizer bands in a barley trial. The study effectively bridges a critical gap between controlled laboratory experiments and field conditions to expand the use of a well-known technique at the bench scale.

The paper's primary strength is the novelty: the deployment of a large-format, robust DGT device to visualize P availability gradients directly in the field. This addresses a known technical limitation in soil science (missing soil heterogeneity during sampling, processing, etc). The methodology is sound and well-described, integrating innovative device design, field application, and advanced synchrotron analysis. The results are promising, providing the first field-visualized evidence of three distinct P reaction zones (saturation plateau, transition, sorption-controlled) within the fertosphere, a phenomenon previously only described in lab studies. The discussion connects findings to potential mechanisms (e.g., precipitation vs. sorption) and compares results to previous laboratory work. I was doubtful regarding the use of new terms like fertosphere, but after seeing the definition, I agree that it can be used in the text.

We thank the anonymous reviewer for their succinct summary of our manuscript and for highlighting the positive contribution that they believe this research can bring to soil science and agricultural research communities.

2. To enhance clarity, impact, and readiness for publication, focus on the following improvements:

Abstract and introduction: Explicitly state the novelty in the Abstract and Introduction. Emphasize that this is the first report of 2D, spatially-resolved P availability mapping obtained in situ (field) at the fertilizer band scale in a dryland crop system.

We thank the review for th advice and will add the following text (underlined) to the Abstract and Introduction:

Abstract: *We believe this is the first report of two-dimensional spatially resolved mapping of P bioavailability obtained in situ (field) at the fertiliser band scale in a dryland cropping system*

Introduction, Page 3: *To the best of our knowledge, such an approach has not been used to investigate the availability of P from fertilisers in field trials of major crops, excluding rice, and specifically not in any dryland cropping systems.*

Introduction, Page 3: *Here, we report the design of a novel field DGT (fDGT) device and its evaluation for visualising and assessing the spatial availability of P from different fertiliser sources in a barley field trial for the first time.*

3. Comment on the discussion: While the mechanistic discussion of the three zones is excellent, as well as the technical aspects of the technique, elevate the discussion by more directly linking spatial findings to agronomic implications. For example, discuss how the identified "saturation plateau" and limited vertical diffusion (10-15 mm) could inform optimal fertilizer granule spacing or band placement to maximize root interception.

Thank you for this suggestion, we will add the following text to the manuscript:

Page 9: *This mechanistic knowledge of how fertilisers behave in the field can be used to drive improvements in management practices and fertiliser formulations, ultimately increasing fertiliser nutrient use efficiency (Lombi et al., 2025). In contrast to the bulk soil, the fertosphere is likely to also have steep gradients for soil pH and EC which can influence nutrient availability. Therefore, by better understanding these spatial* *differences, agronomic practices could be improved by developing fertiliser formulations with a more sustained nutrient supply, in turn reducing precipitation and fixation reactions, and by optimising the placement of fertilisers (Lombi et al., 2025). For example, for this fertiliser-soil combination (i.e. DAP granules in a calcareous soil), if seeds are placed ≤ 5 mm from the fertiliser, primary roots would be exposed to the highest concentration of available P, but increasing the application rate of P may not be beneficial as the P availability plateau has been reached. In addition, although sorption reactions dominate further away from the granule, vertical spacing between fertiliser and seed bands should not exceed 20 mm due to the limited vertical diffusion of P.*

Also, connect the reduced plant biomass at high DAP rates to the discussion, noting that fDGT measures P supply, but other factors (e.g., ammonium toxicity) ultimately determine crop response, if there was any effect that could explain this contrast.

We agree with the reviewer that this is an important point. However, we contend that this has already been addressed in the Discussion at Line 188-192:

Line 188-192: The lower biomass at the higher DAP rate, is possibly due to ammonia/ammonium (NH_3/NH_4^+) toxicity; a known issue when ammoniacal fertilisers are banded in the vicinity of seeds (Pan et al., 2016). A review of the literature in relation to ammonia/ammonium-induced plant toxicity, caused by fertilisers with a high N:P ratio, shows that nutrient uptake, root proliferation and plant biomass can be reduced when NH_3/NH_4^+ accumulate (Sica et al., 2025).

Table 2: I would consider removing the data of soil pH and EC, because at the end you conclude that the changes aren't very clear changes that you can use. And, if you do so, maybe the data of plants can be included in figure 2.

We appreciate this comment and agree that the pH and EC data were minimally impacted by fertiliser application due to potential masking by the bulk sampling protocol (0-4 cm and 4-6 cm). However, we feel there is still value in presenting these data as there were significant differences in pH (albeit minimal) between the two depths. We feel this information is also important for highlighting the importance of shifting from focussing on bulk chemistry to spatially resolved approaches.

Figure 2: Define all abbreviations (DAP, DAP2, Bio) fully within the figure legend itself. I would add here the results of plant P (Table 2) and also I would select a colour for each treatment and light for the upper and dark for the deeper depth, putting in pairs each treatment and maybe the concentration in plant as a line.

We will define all abbreviations in the legend and update the figure. The original colour scheme was 'colourblind safe', but we will insert a new figure (still colourblind safe) where the treatments are paired together as suggested and the colours better show the grouping i.e. light blue and dark blue for shallow and deep sampling depths. For some treatments due to the colourblind safe scheme a light and dark option is not always available but we will reorder the grouping of treatments to make this image clearer as shown in the attached updated figure. New figure caption for Figure 2:

Figure 2. Total P and Colwell P as a function of fertiliser treatment and sample depth (note that P fertiliser was placed 5 cm below the soil surface). Where diammonium phosphate is applied at 10 kg P ha^{-1} (DAP_10) 'DAP_20' is applied at double the rate (i.e. 20 kg P ha^{-1}) and Biochar+DAP is a combination of both materials applied at a total rate of 20 kg P ha^{-1}.

Figure 3: The legend is currently insufficient. It must be self-contained and explicitly describe: (a) what the color scale represents (e.g., P concentration on the binding layer and values, including the numerical range in a scale on the side); and (b) panel caption should be explained, mainly how it was estimated from a 2D to a dispersion of 1 point per depth (one line in the gel? Or the average of different lines in the gel?).

Thank you for picking this up. We will amend the figure caption as suggested to more clearly explain the colour scale and how we averaged the XFM data for each horizontal transect to produce 1 point per depth.

Revised figure caption:

Figure 3. Two dimensional P diffusion images measured using field-deployed DGT in combination with XFM, where (a) are P XFM images of the DGT binding layers collected from the diammonium phosphate treatment where P was applied at 10 kg ha^{-1} (DAP_10), DAP_20 was applied at 20 kg ha^{-1} and the Biochar + DAP treatment (Bio_20) delivered a combined 20 kg P ha^{-1}; and (b) labile P concentrations (Cp, µg P L^{-1}) calculated as a function of depth for the three fertiliser treatment tested (DAP_10, DAP_20, DAP+Biochar); obtained by averaging the 2D XFM maps across the horizontal axis i.e. each coloured point in (b) is the average of the Cp values in a horizontal transect across the gel. Data from two DGT replicates per treatment were collected i.e. "a" and "b". 'Depth' is the distance from the soil surface.

Otherwise, congratulations, the authors have done a great work and this contribution will be of great interest in SOIL journal.

We thank the reviewer for their time taken in reviewing this manuscript and their suggestions to improve its quality.