

UC Davis

UC Davis Previously Published Works

Title

Technical note: An open-source, low-cost system for continuous monitoring of low nitrate concentrations in soil and open water

Permalink

<https://escholarship.org/uc/item/7q0032kt>

Journal

Biogeosciences, 21(12)

ISSN

1726-4170

Authors

Bulusu, Sahiti
García, Cristina Prieto
Dahlke, Helen E
[et al.](#)

Publication Date

2024

DOI

10.5194/bg-21-3007-2024

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

1 **Technical note: An open-source, low-cost system for continuous** 2 **monitoring of low-concentration nitrate ~~monitoring~~ in soil and** 3 **open water**

4 Sahiti Bulusu¹, Cristina Prieto García², Helen E. Dahlke², Elad Levintal^{3,*}

5 ¹ Basis Independent Fremont Upper School, Fremont, CA 94539, USA

6 ² Department of Land, Air and Water Resources, University of California, Davis, CA 95616, USA

7 ³ Zuckerberg Institute for Water Research, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of
8 the Negev, Sde Boker campus, 84990, Israel

9 *Correspondence to:* Elad Levintal (levintal@bgu.ac.il)

10 **Abstract.** Nitrate (NO_3^-), mainly leaching with soil pore water, is the primary nonpoint source pollutant
11 of groundwater worldwide. Obtaining real-time information on nitrate levels in soils would allow gaining
12 a better understanding of the sources and transport dynamics of nitrate through the unsaturated zone.
13 However, conventional nitrate detection techniques (e.g. soil sample analysis) necessitate costly,
14 laboratory-grade equipment for analysis, along with human resources, resulting in a laborious and time-
15 intensive procedure. These drawbacks raise the need to develop cost-effective and automated systems for
16 in situ nitrate measurements in field conditions. This study presents the development of a low-cost,
17 portable, automated system for field measurements of nitrate in soil pore water and open water bodies.
18 The system is based on the spectrophotometric determination of nitrate using a single reagent. The system
19 design and processing software are openly accessible, including a building guide, to allow duplicating or
20 changing the system according to user-specific needs. Three field tests, conducted over five weeks,
21 validated the system's measurement capabilities within the range of 0-10 ppm NO_3^- -N with a low RMSE
22 of <0.2 ppm NO_3^- -N when comparing the results to standard laboratory nitrate analysis. Data derived
23 from such a system allow tracking of the temporal variation in soil nitrate, thus opening new possibilities
24 for diverse soil and nutrient management studies.

25 **1. Introduction**

26 Nitrogen (N) is a macro-nutrient found in soil, groundwater, and open water bodies across the globe.
27 Nitrogen is essential for crop production and applying nitrogen-based fertilizers is a common practice in
28 agriculture. However, excess fertilization leads to low nitrogen use efficiency (NUE) and can cause
29 groundwater contamination due to leaching of excess nitrate (NO_3^-) in the soil, which is the mobile form
30 of nitrogen and is easily transported by water (Ascott et al., 2017; Turkeltaub et al., 2021; Levintal et al.,
31 2023). Nitrate leaching from agricultural soils through the vadose zone has become the primary nonpoint

32 source pollutant of groundwater (Ascott et al., 2017; Richa et al., 2022; Gurdak and Qi, 2012). Elevated
33 nitrate concentrations in open water, in addition to groundwater, are also considered a major global threat
34 that can cause algae blooms and loss of aquatic life (Van Metre et al., 2016; Wherry et al., 2021).

35 Optimizing fertilization by applying the needed amount of nitrogen fertilizer for the crop at each growing
36 stage can reduce the environmental risks above. To achieve this, real-time information on soil pore water
37 nitrate levels is required (Yeshno et al., 2019), leading to a need for an accessible method to measure real-
38 time nitrate concentrations in soils. However, measuring continuous in situ soil pore water nitrate
39 concentrations is still a major environmental and agricultural challenge. During the last two decades,
40 different soil pore water nitrate characterization technologies were tested, including ion-selective
41 electrodes, portable spectrophotometers coupled with suction cups, and lab-on-a-chip technologies
42 (Bristow et al., 2022).

43 The majority of published nitrate sensing systems for soil pore water show promising directions,
44 however, they are limited to only lab tests, require complicated and repeated calibration procedures, or
45 may be considered as a proof-of-concept rather than a functional field system (e.g., Ali et al., 2019; Chen
46 et al., 2023; Tuli et al., 2009). Only two published studies, as far as we know, showed significant progress
47 in measuring soil pore water nitrate concentrations continuously in the field. Bristow et al. (2022)
48 developed ion-selective electrodes for soil nitrate sensing. The electrodes were field tested under a
49 relatively high nitrate measurement range of ~50-300 ppm NO_3^- -N with a reported Root Mean Square
50 Error (RMSE) of ~16 ppm NO_3^- -N. They described significant drift after eight weeks of field deployment
51 that required the development of a correction algorithm. In general, electrode fouling, drift, ion
52 interference, limited sensitivity, and the need for temperature compensation are major disadvantages of
53 ion-selective electrodes (Tuli et al., 2009).

54 Yeshno et al. (2019) presented a monitoring system for continuous measurements of nitrate
55 concentrations in soil pore water. Their system is based on ultraviolet (UV) absorbance spectroscopy to
56 directly determine nitrate without pretreatment of the sample, such as filtration or adding reagents. The
57 system was tested at four agricultural field sites during four sampling campaigns. The nitrate
58 measurement range was ~10-350 ppm NO_3^- -N (no RMSE was reported). The main advantage of the
59 system is the durability and lack of needed field calibration, thus we consider this system as the most
60 advanced and robust solution for field nitrate measurements currently available. Yet, the methodology is
61 patented with no assembly details provided, and therefore, it cannot be duplicated and deployed by other
62 users.

63 This study describes the construction and performance of a portable, low-cost, automated system for pore
64 water nitrate measurements. The system is based on a spectrophotometer coupled with an array of pumps
65 and a suction cup installed in the soil. A comprehensive technical documentation encompassing system
66 design, assembly, programming, deployment, power management, and data analysis is included to allow
67 end-users to replicate, modify, and deploy the system to their specific requirements without requiring
68 prior engineering expertise. For validation, three field tests with a concentration range of 0-10 ppm NO₃⁻-
69 N were conducted over five weeks.

70 2. Materials and Methods

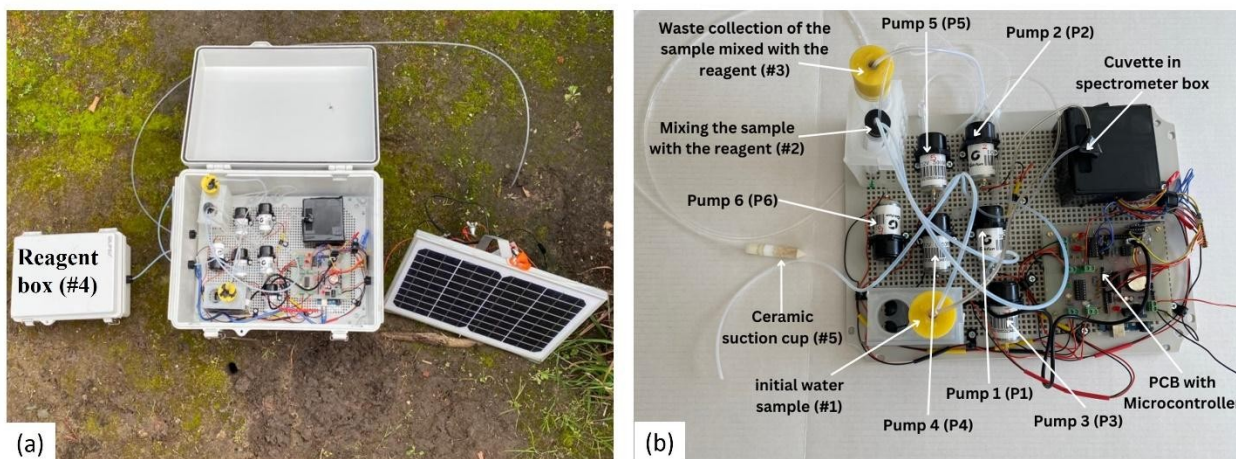
71 The system is based on the spectrophotometric determination of nitrate using a single reagent (Doane and
72 Horwath, 2003). Each water sample is mixed with a reagent (Vanadium(III) chloride (VCl₃) +
73 Sulfanilamide + N-(1-naphthyl)ethylenediamine dihydrochloride (NEDD)) and then measured at 540 nm
74 wavelength. The absorption intensity is used to determine the nitrate concentration using a calibration
75 curve as detailed below.

76 2.1. Hardware

77 The field nitrate sensing system is established on the open-source hardware concept (Pearce, 2012, 2014)
78 and consists of three segments: the spectrophotometer, the hydraulics system, and the control unit (**Fig.**
79 **1a**). The low-cost spectrophotometer is based on the design by Laganovska et al. (2020), utilizing the
80 C12880MA mini-spectrometer chip (Hamamatsu Photonics K.K., Japan). The device measures
81 absorption in the 450-750 nm range, yet we use only the 540 nm wavelength. The 3D-printed
82 measurement box holds the cuvette for sample measurements (**Fig. 1b**).

83 The hydraulics system consisted of six peristaltic dosing pumps, a set of 1/16" (1.57 mm) inner diameter
84 tubing, a 50 mL container for collecting the initial water sample (#1), a 15 mL container for mixing the
85 sample with the reagent (#2), a 50 mL container for post-processing waste collection of the sample mixed
86 with the reagent (#3), a reagent box (#4), and a ceramic suction cup used to collect the water samples
87 from the tested soil or water body (#5) (**Fig. 1a** and **1b**). The first pump (P1) is connected to the ceramic
88 suction cup for sample collection. The rest of the pumps work in coordination to mix the appropriate
89 sample volume with reagents, deposit it in the cuvette, and then clean the tubes and cuvette once the
90 measurement is taken. The spectrophotometer and hydraulics system are controlled using an open-source
91 microcontroller (Arduino Mega, Arduino, Italy) with a micro-SD card for data logging. The system is
92 powered by a 12 V, 7 Ah battery connected to a 10 W solar panel. Hardware details, system assembly

93 instructions, and pumps sequence are provided on our GitHub page
94 <https://github.com/SahitiB/AGNET/tree/main>.

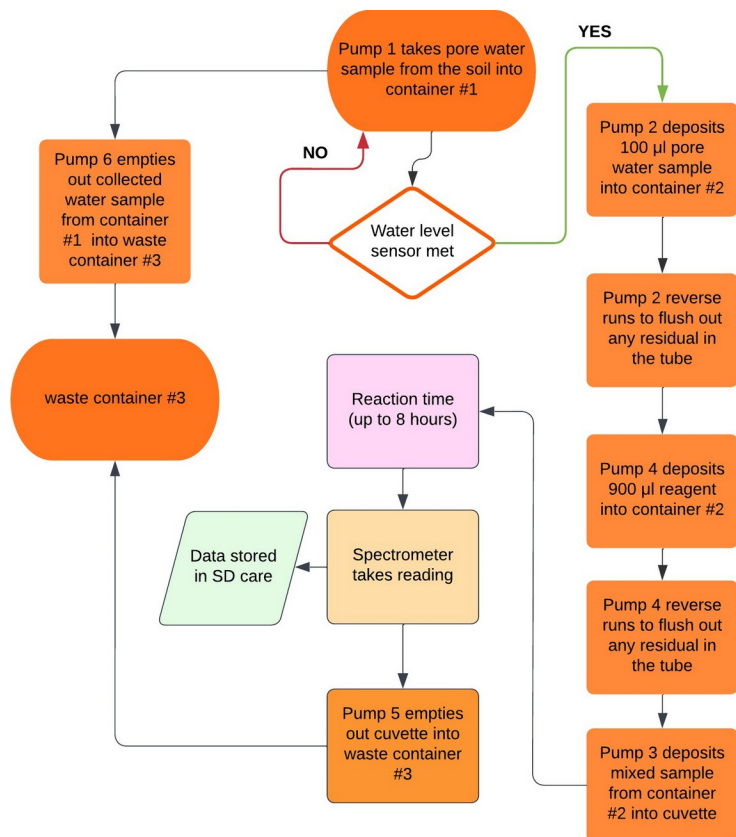


95 (a)
96 **Figure 1.** Experimental setting. The complete system during soil testing (a) and zoom in on the main box
97 (b). We note that the spectrophotometer unit is based on the design by Laganovska et al. (2020).

98 2.2. Software

99 An Arduino Mega microcontroller controls the device. Programming the Mega is done using C++, the
100 default language of the Arduino Integrated Development Environment (IDE)
101 (www.arduino.cc/en/software). The code contains the functions required to control the sequence of events
102 for the entire system as well as the process of the spectrophotometer's results. The order and runtime of
103 the pumps are controlled through the code and can be changed as needed. The complete code and open
104 license conditions are described in our Github page <https://github.com/SahitiB/AGNET/tree/main>.

105 The flowchart in **Fig. 2** shows the sequence of a single nitrate measurement event, as instructed by the
106 code. First, P1 pumps a soil pore water sample through the ceramic suction cup into container #1 until the
107 water level sensor attached to the container is met at a sample volume of 5 mL. Then, P2 pumps 0.1 mL
108 of the collected sample into container #2, followed by P4 pumping 0.9 mL of the reagent (~~Vanadium-III~~
109 ~~Chloride~~) into the same container #2. The mixed sample is then transported to the cuvette (**Fig. 1b**, black
110 box) using pump P3. Once the passive reaction time of 8 hr is completed, the spectrophotometer reading
111 is taken and pumps P5 and P6 vacuum empty out the cuvette and container #1, and the entire system is
112 thoroughly cleaned, emptied, and readied for the next cycle. The user can change the frequency between
113 nitrate measurement events according to needs and battery consumption as detailed below.



114

115 **Figure 2.** A flow chart of the main sequence in a single nitrate measurement event. A more detailed
 116 description for each step is given on our GitHub page.

117 2.3. Field deployment

118 The system was calibrated using standard nitrate samples of 0, 0.1, 0.3, 1, 3, 5, 8, and 10 ppm NO₃⁻-N.
 119 After running those samples mixed with reagent through the spectrophotometer, a calibration curve
 120 (Beer-Lambert curve) is created relating the spectrophotometer absorbance values vs. the standard nitrate
 121 samples. A calibration curve is constructed before each experiment. Three field tests were conducted to
 122 evaluate system performance – two tests were run on soil pore water samples and one using open water
 123 samples. The tests were all carried out in Fremont, California, between February and June 2023. For each
 124 test, field-measured nitrate concentrations were compared against laboratory measurements with a
 125 Shimadzu 206-24000-92 UV/Visible scanning spectrophotometer at the University of California, Davis
 126 for validation. For the validation, sub-samples were directly taken from the water sample container (#1)
 127 after the pore water sample was obtained but before adding the reagent. Comparison of the field-measured
 128 nitrate with the standard laboratory method was done in several ways.

129 First, we conducted the variable test, which aimed at testing the accuracy of the system by randomly
 130 varying the amount of nitrate fertilizer in the soil during irrigation (Scotts Liquid Turf Builder with Plus 2
 131 Weed Control (25% nitrogen content), Scotts, USA). This tested the ability of the system to detect shifts
 132 in nitrate levels. Secondly, a continuous test was performed to examine the system stability under rain
 133 conditions and the ability to measure nitrate leaching in soil. The variable test ran for seven days with two
 134 readings per day, and the continuous test ran for 17 days with one reading per day. In both tests, the
 135 suction cup was installed at a depth of 6.3 cm (2.5 in) in the soil, and the system operated autonomously
 136 without any maintenance. The third test was the open water pulse test to validate the ability of the system
 137 to measure nitrate in water bodies (e.g., rivers and lakes). The suction cup was submerged in a 12 L water
 138 bucket for 12 days with one reading per day. Every fourth day, a 0.5 L cup of nitrate-based fertilizer
 139 (same as above) was added to the water bucket to test the ability of the system to detect changes in nitrate
 140 levels in open water. Atmospheric measurements for the experiments were taken from the California
 141 Irrigation Management Information System station (CIMIS; station 171 Union City, CA).

142 3. Results and Discussion

143 3.1. System performances

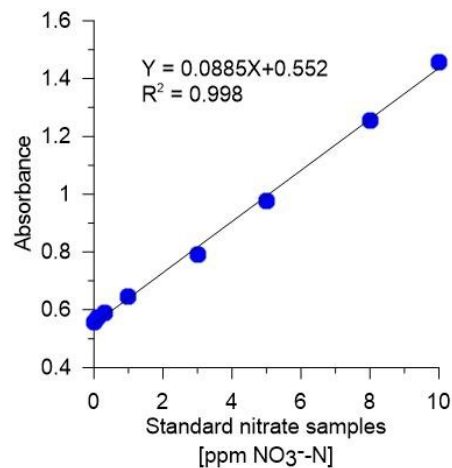
144 A summary of the calibration and experimental results is presented in Table 1. One example of the Beer-
 145 Lambert calibration curve is displayed in **Fig. 3**. The high R^2 of 0.998 between the absorption and the
 146 standard nitrate samples validates the linearity of our spectrophotometer and the capability to accurately
 147 measure nitrate.

148 **Table 1.** Summary of the calibration and experiment results

Experiment type	Duration and sampling rate [d]	Range of tested nitrate [ppm NO ₃ ⁻ -N]	Average RMSE [ppm NO ₃ ⁻ -N]
Calibration	One day	0-10	n/a
Soil variable test	Seven days (twice per day) 13/2/2023-19/2/2023	0-0.97	0.09
Soil continuous test	17 days (once per day) 28/2/2023-16/3/2023	0-2.39	0.10
Open water pulse	12 days (once per day)	0-7.29	0.20

test	10/6/2023-21/6/2023		
------	---------------------	--	--

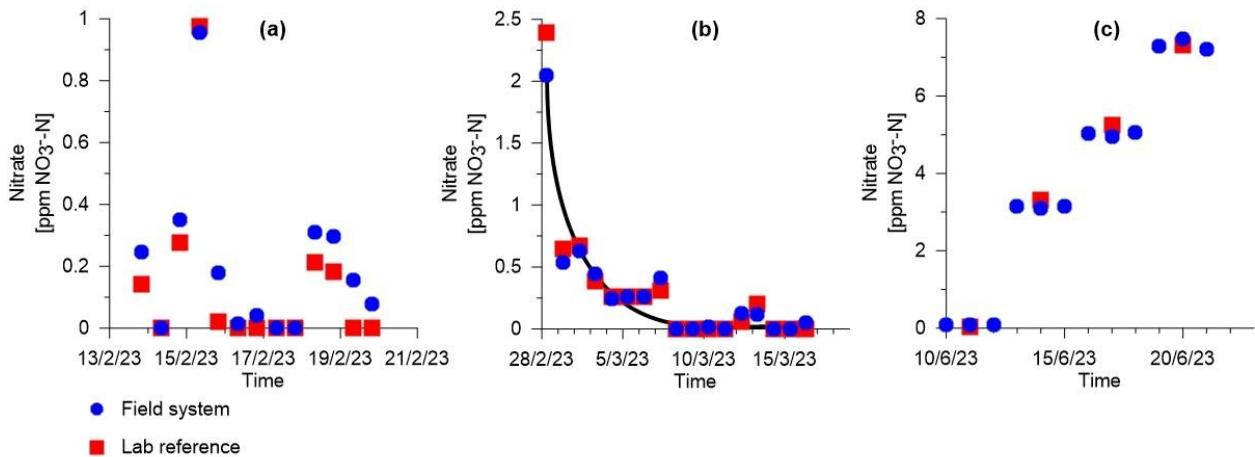
149



150

151 **Figure 3.** Beer-Lambert calibration curve for the system spectrophotometer using known standard nitrate
 152 concentrations of 0, 0.1, 0.3, 1, 3, 5, 8, and 10 ppm of NO₃⁻-N.

153 The first variable test focused on the low range of nitrate in the soil < 1 ppm NO₃⁻-N. During the seven-
 154 day test, the system was successful in measuring the changes in nitrate level with a RMSE of 0.09 ppm
 155 NO₃⁻-N compared to the lab reference analysis (**Fig. 4a**). We consider this as a low error value that
 156 validates our system in the low concentration range of nitrate. The soil continuous test showed similar
 157 high accuracy throughout the 17 days of trial with an average RMSE of 0.10 ppm NO₃⁻-N (**Fig. 4b**). The
 158 stability of measurements during this period suggests that no degradation of system performance was
 159 occurring with all measurement cycles conducted successfully. This 17-day test was conducted during a
 160 significant rain event with 12.2 mm d⁻¹ of rainfall occurring on the first day. Therefore, we were able to
 161 measure, in real-time, the nitrate leaching in the topsoil (marked by the black curve line in **Fig. 4b**). The
 162 third test was conducted to validate the system in open water (**Fig. 4c**). In this case, the suction cup was
 163 submerged in a 12 L water container, and nitrate-based fertilizer was added every fourth day. RMSE
 164 remained low with 0.20 ppm NO₃⁻-N. The first step of water sampling using P1 was drastically faster
 165 compared to the soil tests, reducing the pump time from 30-40 min to 5-10 min per cycle.



166

167 **Figure 4.** Experimental results of the spectrophotometer testing for the soil variable test of low nitrate
 168 concentrations (a), the soil continuous test under a rain event (b), and the open water pulse test (c). The
 169 black line in subplot (b) marks the nitrate leaching after a rain event of 12.2 mm d^{-1} on 28/2/2023. For
 170 each concentration level in the open water pulse test in subplot (c), three field measurements (blue dots)
 171 were compared to one laboratory measurement (red squares).

172 3.2. System limitations and modifications

173 In this study, we presented and tested a portable, low-cost field nitrate sensing system to measure in situ
 174 nitrate concentrations in soil pore water and aquatic environments. Although the system is autonomous in
 175 terms of obtaining a sample and processing it until a nitrate concentration is determined, it does require
 176 some user input. The main user input required involves replacing the dry ice in the reagent box to
 177 maintain the recommended temperature of $4 \text{ }^{\circ}\text{C}$ for the Vanadium III Chloride reagent to work at its
 178 optimum (**Fig. 1a**). In our experiments, replacing the dry ice every five days was sufficient to ensure this
 179 temperature, however, all experiments were conducted at an average daily air temperature of $10 \text{ }^{\circ}\text{C}$ with a
 180 daily maximum of $\sim 20 \text{ }^{\circ}\text{C}$. Warmer conditions will require a more frequent replacement time of the dry
 181 ice or adding a cooler box or more advanced solutions, such as a small field refrigerated unit or a
 182 [Peltier cooling plate](#) based on solar panel or gas. Improving the reagent chill-box will increase
 183 system cost yet reduce human dependency. This, together with the addition of a low-cost modem or
 184 wireless communication such as Wifi or LoRa (Bristow et al., 2022; Sanchez-Iborra et al., 2018; Levintal
 185 et al., 2021), will make the device completely autonomous for weeks to months.

186 The system, considering our sample to reagent ratio, can accurately measure nitrate concentrations up to
 187 $\sim 10 \text{ ppm NO}_3^{-}\text{-N}$. This is a well-known limitation- ([Doane and Horwath, 2003](#)) of using the Vanadium III
 188 Chloride reagent, which also exists in the lab. It would be possible to increase the range with the current

189 system by either increasing the amount of reagent, decreasing the amount of sample, or both. However,
190 further experiments will ~~would~~ be necessary to implement and test ~~provide an accurate~~ this extended range.
191 When analyzing samples with higher concentrations (70-80 ppm), adding the reagent results in unusual
192 colors (salmon, orange, and yellow) ~~turns the water sample to colors~~ that cannot be accurately measured
193 and calibrated using known concentration standards and the spectrophotometer ~~(Doane and Horwath,~~
194 2003). For example, a sample with a high concentration (e.g., approximately ~~over~~ 1200 ppm NO₃-N)
195 will turn yellow and the spectrophotometer will register absorbance corresponding to concentrations
196 lower than 1 ppm NO₃-N, indicating a false reading. ~~read absorbance around 0.250, corresponding to a~~
197 false concentration reading lower than 1 ppm NO₃-N. A possible solution could be the addition of a
198 visual color sensor to notify the user when the color is ~~out of range~~ exceeding the concentration range
199 covered by the standard (i.e., high nitrate concentrations) to then dilute the sample accordingly. This will
200 require changing the design of the system and adding a dilution mechanism.

201 If a high measurement frequency is required, a heating device can be added, or a temperature curve can be
202 developed to reduce the 8-hour reaction time of the Vanadium III Chloride reagent in the cuvette. Yet,
203 this need is highly site-specific as warmer climates will reduce the sample-reagent time naturally. Higher
204 measurement frequency means higher power consumption, which should be optimized using a larger
205 battery capacity and/or a larger solar panel. In our experiments, taking the soil variable test as a reference
206 (**Fig. 4a**), the 12 V, 7 Ah with a 10 W solar panel was sufficient for two samples per day for seven
207 continuous days. This was achieved under cloudy skies with an average daily solar radiation of 156 W m⁻².
208 Power consumption is site-dependent due to the variability in the solar panel's efficiency to charge a 12
209 V battery, and moreover, due to the changes in soil moisture. Lower soil moisture will increase the run
210 time of the peristaltic pump extracting the water sample from the soil (P1 in **Fig. 1**), therefore increasing
211 power consumption for each nitrate sampling cycle. In very dry conditions, water samples cannot be
212 extracted from the soil and the system will not work. A possible optimization solution could be the
213 addition of a soil moisture sensor to deactivate the system under very dry conditions. We note that this is
214 a common problem of using suction cups in dry soils unrelated to this specific system.

215 This study demonstrates the capabilities to measure nitrate leaching during a rain event and nitrate
216 changes in open water. Additional potential research objectives for the low-cost portable nitrate system
217 include: (1) measuring soil nitrate levels in the root zone of an agricultural field during a growing session
218 to optimize nitrogen fertilization applications, i.e., precision agriculture methods to reduce groundwater
219 pollution (Yeshno et al., 2019). This application will need to include a soil moisture sensor to allow the
220 calculation of the nitrate stock available for plant uptake (Bristow et al., 2022); (2) couple the system with

221 low-cost oxygen sensors (Levintal et al., 2022) to investigate in real time the occurrence of denitrification
222 and its dependency on soil oxygen levels (Levintal et al., 2023); (3) measure nitrate changes in
223 lakes/rivers during heavy rain events or floods, and (4) implementing the same design to measure other
224 contaminants in the soil pore water and open water given that they have distinct absorbance in the range
225 of our spectrophotometer of 450-750 nm.

226 **4. Summary**

227 This study presents the development of a low-cost, portable, automated system for field measurements of
228 nitrate in soil pore water and open water bodies. The system consists of an Arduino-controlled array of
229 pumps, a suction cup installed in the soil, and a spectrophotometer that measures the nitrate concentration
230 after the water sample is mixed with a reagent. Three field tests conducted over five weeks to validate the
231 system within a measurement range of 0-10 ppm NO_3^- -N showed a low RMSE of <0.2 ppm NO_3^- -N when
232 comparing the results to standard laboratory nitrate analysis. This nitrate range is suitable for soils with
233 low nitrate concentrations or open water. The system design and processing software are openly
234 accessible. By designing a system in which all electronics are limited to buyable hardware components
235 and the files for the printed circuit board (PCB) are provided, it is possible to duplicate or change the
236 system according to user-specific needs. The total cost of the system components is USD \$1,100,
237 excluding reagents, which we hope will allow reproducibility and open new possibilities for conducting
238 field studies in soil and environmental nitrate monitoring.

239 **Code and data availability**

240 The complete technical guide and code are available in our GitHub repository
241 (<https://github.com/SahitiB/AGNET/tree/main>)

242 **Author contributions**

243 EL conceptualized the study and designed the system, SB constructed the system and conducted the
244 study, SB and EL wrote the first manuscript draft, HED provided the resources and project supervision.
245 All the authors (SB, CPG, HED, and EL) contributed to the final version.

246 **Competing interests**

247 The contact author has declared that none of the authors has any competing interests.

248 **Acknowledgments**

249 This research has been supported by the Gordon and Betty Moore Foundation (grant no. 7975), the
250 United States–Israel Binational Agricultural Research and Development Fund (Vaadia-BARD
251 Postdoctoral Fellowship no. FI-605-2020), and the USDA National Institute of Food and Agriculture
252 grant no. 2021-68012-35914.

253 **References**

254 Ali, M. A., Wang, X., Chen, Y., Jiao, Y., Mahal, N. K., Moru, S., Castellano, M. J., Schnable, J. C.,
255 Schnable, P. S., and Dong, L.: Continuous Monitoring of Soil Nitrate Using a Miniature Sensor with
256 Poly(3-octyl-thiophene) and Molybdenum Disulfide Nanocomposite, *ACS Appl. Mater. Interfaces*, 11,
257 29195–29206, <https://doi.org/10.1021/acsami.9b07120>, 2019.

258 Ascott, M. J., Gooddy, D. C., Wang, L., Stuart, M. E., Lewis, M. A., Ward, R. S., and Binley, A. M.:
259 Global patterns of nitrate storage in the vadose zone, *Nat. Commun.*, 8, 1–6,
260 <https://doi.org/10.1038/s41467-017-01321-w>, 2017.

261 Bristow, N., Rengaraj, S., Chadwick, D. R., Kettle, J., and Jones, D. L.: Development of a LoRaWAN
262 IoT Node with Ion-Selective Electrode Soil Nitrate Sensors for Precision Agriculture, *Sensors*, 22, <https://doi.org/10.3390/s22239100>, 2022.

264 Chen, S., Chen, J., Qian, M., Liu, J., and Fang, Y.: Low cost, portable voltammetric sensors for rapid
265 detection of nitrate in soil, *Electrochim. Acta*, 446, 142077,
266 <https://doi.org/10.1016/j.electacta.2023.142077>, 2023.

267 Doane, T. A. and Horwath, W. R.: Spectrophotometric determination of nitrate with a single reagent,
268 *Anal. Lett.*, 36, 2713–2722, <https://doi.org/10.1081/AL-120024647>, 2003.

269 Gurdak, J. J. and Qi, S. L.: Vulnerability of Recently Recharged Groundwater in Principle Aquifers of
270 the United States To Nitrate Contamination, *Environ. Sci. Technol.*, 46, 6004–6012,
271 <https://doi.org/10.1021/es300688b>, 2012.

272 Laganovska, K., Zolotarjovs, A., Vázquez, M., Mc Donnell, K., Liepins, J., Ben-Yoav, H., Karitans, V.,
273 and Smits, K.: Portable low-cost open-source wireless spectrophotometer for fast and reliable
274 measurements, *HardwareX*, 7, e00108, <https://doi.org/10.1016/j.ohx.2020.e00108>, 2020.

275 Levintal, E., Lee Kang, K., Larson, L., Winkelman, E., Nackley, L., Weisbrod, N., Selker, J. S., and
276 Udell, C. J.: eGreenhouse: Robotically positioned, low-cost, open-source CO₂ analyzer and sensor device
277 for greenhouse applications, *HardwareX*, 9, e00193, <https://doi.org/10.1016/j.ohx.2021.e00193>, 2021.

278 Levintal, E., Ganot, Y., Taylor, G., Freer-Smith, P., Suvocarev, K., and Dahlke, H. E.: An underground,
279 wireless, open-source, low-cost system for monitoring oxygen, temperature, and soil moisture, *Soil*, 8,
280 85–97, <https://doi.org/10.5194/soil-8-85-2022>, 2022.

281 | Levintal, E., Huang, L., [Prieto](#) García, C.-P., Coyotl, A., Fidelibus, M. W., Horwath, W. R., Mazza

282 Rodrigues, J. L., and Dahlke, H. E.: Nitrogen fate during agricultural managed aquifer recharge: Linking
283 plant response, hydrologic, and geochemical processes, *Sci. Total Environ.*, 864, 161206,
284 <https://doi.org/10.1016/j.scitotenv.2022.161206>, 2023.

285 Van Metre, P. C., Frey, J. W., Musgrove, M., Nakagaki, N., Qi, S., Mahler, B. J., Wiczorek, M. E., and
286 Button, D. T.: High Nitrate Concentrations in Some Midwest United States Streams in 2013 after the
287 2012 Drought, *J. Environ. Qual.*, 45, 1696–1704, <https://doi.org/10.2134/jeq2015.12.0591>, 2016.

288 Pearce, J. M.: Building Research Equipment with Free, Open-Source Hardware, *Science (80-.)*, 337,
289 1303–1304, <https://doi.org/10.1126/science.1228183>, 2012.

290 Pearce, J. M.: Cut costs with open-source hardware, *Nature*, 505, 618–618,
291 <https://doi.org/10.1038/505618d>, 2014.

292 Richa, A., Touil, S., and Fizir, M.: Recent advances in the source identification and remediation
293 techniques of nitrate contaminated groundwater: A review, *J. Environ. Manage.*, 316, 115265,
294 <https://doi.org/10.1016/j.jenvman.2022.115265>, 2022.

295 Sanchez-Iborra, R., Sanchez-Gomez, J., Ballesta-Viñas, J., Cano, M. D., and Skarmeta, A. F.:
296 Performance evaluation of lora considering scenario conditions, *Sensors*, 18,
297 <https://doi.org/10.3390/s18030772>, 2018.

298 Tuli, A., Wei, J., Shaw, B. D., and Hopmans, J. W.: In Situ Monitoring of Soil Solution Nitrate: Proof of
299 Concept, *Soil Sci. Soc. Am. J.*, 73, 501–509, <https://doi.org/10.2136/sssaj2008.0160>, 2009.

300 Turkeltaub, T., Jia, X., Zhu, Y., Shao, M., and Binley, A.: A Comparative Study of Conceptual Model
301 Complexity to Describe Water Flow and Nitrate Transport in Deep Unsaturated Loess, *Water Resour.*
302 *Res.*, 57, 1–21, <https://doi.org/10.1029/2020WR029250>, 2021.

303 Wherry, S. A., Tesoriero, A. J., and Terziotti, S.: Factors Affecting Nitrate Concentrations in Stream
304 Base Flow, *Environ. Sci. Technol.*, 55, 902–911, <https://doi.org/10.1021/acs.est.0c02495>, 2021.

305 Yeshno, E., Arnon, S., and Dahan, O.: Real-time monitoring of nitrate in soils as a key for optimization
306 of agricultural productivity and prevention of groundwater pollution, *Hydrol. Earth Syst. Sci.*, 23, 3997–
307 4010, <https://doi.org/10.5194/hess-23-3997-2019>, 2019.

308

309