A new drought monitoring network in the state of Brandenburg (Germany) using cosmic-ray neutron sensing

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Abstract.

In the recent years, the German federal state of Brandenburg has been particularly impacted by soil moisture droughts. To support the timely and informed management of such water-related risks, we introduce a novel soil moisture and drought monitoring network based on cosmic-ray neutron sensing (CRNS) technology. This initiative is driven by a joint collaboration of research institutions and federal state agencies, and it is the first of its kind in Germany to have started operation. In 2024, eight sites were instrumented across Brandenburg; four more are about to be deployed by mid 2025. The data is openly accessible in order to foster applications and collaboration right from the start. In this paper, we present the network design, evaluate the CRNS-based soil moisture estimation, and demonstrate how the inherent limitations of a sparse instrumental soil moisture network - such as limited temporal and spatial coverage - could be mitigated by the use of a soil hydrological model. We further discuss practical lessons learned from the establishment and operation of the network, as well as potential future applications.

1 Introduction

Soil moisture acts as a key state variable in the earth system: it exerts a major control on evapotranspiration, and hence the exchange of water and energy between soil and atmosphere. Furthermore, soil moisture affects the vitality and productivity of natural vegetation as well as agricultural systems, and influences groundwater recharge, runoff formation, and the emission and sequestration of soil organic carbon.

The importance of soil moisture, and hence its monitoring, becomes specifically obvious in Brandenburg as one of the driest federal states in Germany. Large parts of the state are governed by relatively low annual precipitation sums (between 500 and 700 mm/a) and permeable sandy soils with low water retention capacity. This combination entails various drought-related hazards which became particularly obvious in the years 2018 to 2022. In this period, Brandenburg was affected by declining groundwater tables (Pohle et al., 2024; Warter et al., 2024), wild fires (Priesner et al., 2024), forest degradation (Horn et al., 2025; Priesner et al., 2024), and crop yield losses (Brill et al., 2024). While locations with a deep groundwater table are particularly prone to drought effects on vegetation, Brandenburg additionally features extensive lowland and wetland areas with shallow groundwater tables. In these areas, evapotranspiration in summer is particularly high, which causes a substantial pressure on water availability in lakes and rivers (Pohle et al., 2024; Warter et al., 2024). Again, this process is regulated by root-zone soil moisture.

Although the necessity of soil moisture monitoring is widely acknowledged (Oswald et al., 2024), it remains a notorious challenge to obtain timely and reliable data at useful spatio-temporal coverage and resolution. Conventional point-scale sensors are invasive and suffer from a lack of spatial representativeness, while remote sensing products are limited by shallow penetration depths, low overpass frequencies, and vegetation-related uncertainties (Babaeian et al., 2019; Schmidt et al., 2024; Oswald et al., 2024).

Within the past decade, cosmic-ray neutron sensing (CRNS) has emerged as a promising alternative (Andreasen et al., 2017). It allows for continuous and non-invasive monitoring of soil moisture with a measurement depth of tens of centimeters ("the root zone") and a footprint area of approximately 10 hectares (e.g. Schrön et al., 2017). When operated in mobile mode, the spatial extent of the CRNS measurement can be increased substantially, depending on the carrying vehicle (e.g., Altdorff et al., 2023).

With these features, CRNS is an ideal candidate to fill a critical scale gap in soil moisture observations, as it enables robust estimates that are representative at the scale of agricultural fields, hydrotopes, or typical landscape parcels. In a densely instrumented agricultural research site near Potsdam (Brandenburg), Heistermann et al. (2023) already demonstrated the capability of multiple CRNS sensors to consistently capture the prolonged soil moisture droughts during the years 2019, 2020, and 2022.

So far, however, CRNS has mainly been used in experimental contexts, i.e. measurements are often carried out for limited periods of time, and resulting soil moisture time series are often not shared with the general public. Only few countries have already established long-term CRNS monitoring networks at the national scale (e.g., the USA, UK). For Germany, such a nationally coordinated effort is not yet in place, although some regions have been instrumented as part of the TERENO observatories (Zacharias et al., 2024). In the agricultural context, CRNS is already being used to monitor selected cropland sites in parts of the federal state of North Rhine-Westphalia (Ney et al., 2021).

The first attempt in Germany to systematically apply CRNS technology at the federal state level was initiated in 2024 when a consortium of research institutions and state agencies was formed in order to design, implement and maintain a CRNS-based soil moisture and drought monitoring network for the state of Brandenburg. The aim of this network is to provide a comprehensive monitoring approach at the state level, covering landscape units that are representative for the main land use and soil types and also for diverse groundwater conditions found in Brandenburg.

At the same time, any such instrumental effort for soil moisture monitoring is necessarily and inherently limited: concerning its temporal, vertical and horizontal coverage as well as with regard to its ability to represent the surface water balance. Hydrological models have the potential to overcome such limitations (Oswald et al., 2024), yet the lack of representativeness

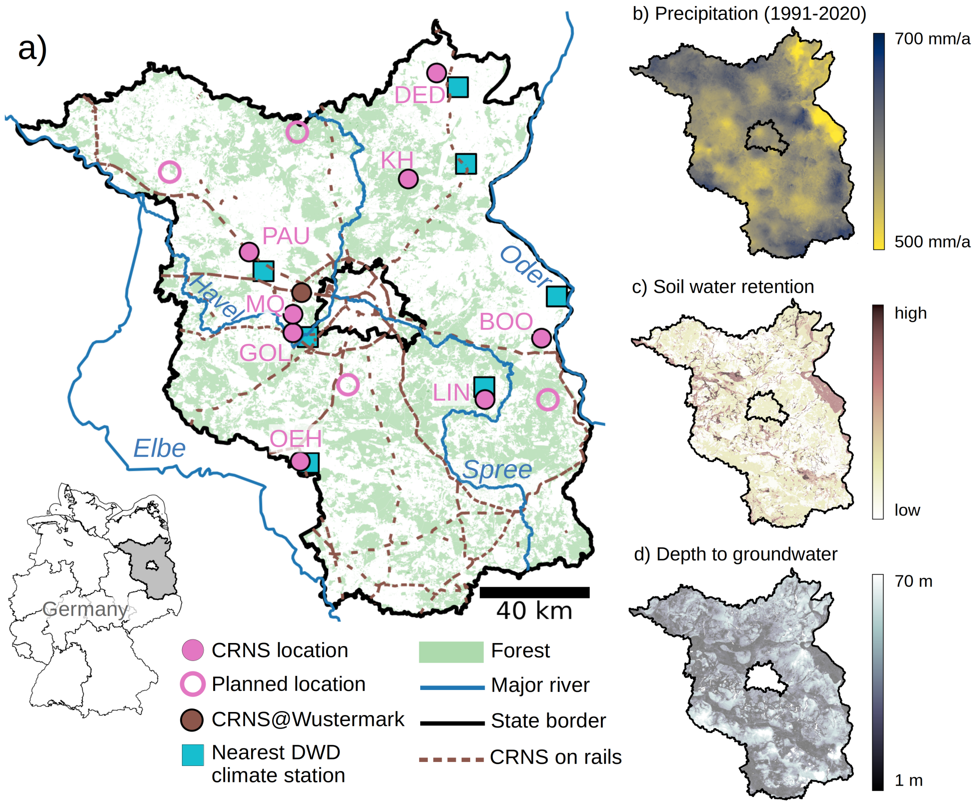

Figure 1. (a) Current locations of CRNS-based soil moisture monitoring network (filled pink dots), planned locations (hollow pink dots) nearest DWD climate stations (turquoise squares), forest coverage (green shade, © OpenStreetMap contributors, 2024, distribution under ODbL license), and rail-based CRNS network (brown). The labels show the location IDs in reference to Tab. 1. (b–d) Spatial distribution of other geographical attributes across Brandenburg: mean annual precipitation (1991-2020, based on DWD's HYRAS-PRE data), top soil water retention capacity (LBGR, 2024), and depth to the groundwater table (LfU, 2013).

of conventional point-based soil moisture sensors has so far limited the potential of putting model and observation into context. The advent of CRNS and its statewide deployment might present a new opportunity for such endeavours.

Hence, the specific aims of this paper are as follows:

1. To introduce the new CRNS-based soil moisture monitoring network in Brandenburg to the community as a contribution for future research and applications;
2. To demonstrate the estimation of soil moisture from neutron count rates based on a procedure referred to as general calibration (Heistermann et al., 2024), and evaluate these estimates based on independent reference observations;

3. To demonstrate the potential of contextualising model and observation: to that end, we implement a soil hydrological model at each monitoring location, evaluate its performance by using the observed soil moisture, and exemplify its ability to extend the spatial and temporal coverage of the measurements;

4. To discuss some practical lessons learned from the establishment and operation of the network, as well as potential future applications.

2 Data and methods

2.1 The monitoring network

In a transdisciplinary effort, five institutions have combined their resources to establish a CRNS-based network for soil moisture and drought monitoring in Brandenburg: the Helmholtz Centre for Environmental Research (UFZ), the University of Potsdam (UP), the Ministry of Agriculture, Environment and Climate Protection (MLUK), the State Agency for Mining, Geology and Resources (LBGR), and the State Environment Agency (LfU). Other institutions (namely the Leibniz Centre for Agricultural Landscape Research, and the State Forestry Agency) as well as private land owners contributed by providing the permission to use suitable monitoring sites. The network is designed as a long-term monitoring effort, facilitated by the close collaboration between state agencies and research institutions in which the latter took the initial lead in instrumentation, maintenance, data processing, and dissemination, while the state agencies are progressively assuming such responsibilities.

In the first half of 2024, eight locations (see Fig. 1 and Tab. 1) were equipped with a CRNS station. Such a station includes a neutron detector, logger and telemetry, solar power supply, and sensors for barometric pressure, temperature, and humidity, as well as conventional point-scale sensors of soil moisture in various measurement depths as an additional reference. Five of these stations were instrumented in the first half of 2024, three had already been operational before (Lindenberg since 2020, Marquardt and Oehna since 2022). Four additional locations are designated for instrumentation in spring 2025. For the selection of sites, various criteria had to be accounted for:

- The locations should represent combinations of landscape attributes such as land use (e.g., coniferous forest, meadow, cropland), soil types, or depth of the groundwater table that are representative for the state of Brandenburg.

- Sensor footprint that are homogeneous with regard to these attributes are preferable with regard to the interpretation of the CRNS signal.

- Accessibility and permission of the land owner to place and maintain a CRNS station.

- Availability of security measures against theft or vandalism, typically by fences and limited visibility of the equipment from roads and other public places.

- Sufficient network coverage for remote data transmission.

– Existing additional instrumentation (e.g., by groundwater level sensors, lysimeters, climate gauges, complementary soil moisture measurements) was not mandatory, but advantageous.

– Another optional criterion was the relative proximity to railway tracks. A pilot study in the Harz mountains in central Germany has recently demonstrated that rail-based CRNS can monitor soil moisture along landscape transects of several kilometres at daily resolution (Altdorff et al., 2023). Building on this concept, four additional rail-based CRNS systems are now operational in Brandenburg (Fig. 1) and adjacent federal states. Almost each day, these systems collect soil moisture data along hundreds of kilometres (although the routes vary, depending on the operational schedule), and transmit the data in near real-time. Although this approach is still in its early stage, monitoring locations placed close to railway tracks will enable future comparisons of measurements by overlapping sensor footprints.

Table 1. Overview of CRNS-based monitoring locations. Land use from OpenStreetMap contributors (2024); soil texture classes from BUEK300 (LBGR, 2024): Sl2 (loamy sand), fSms (fine sand), mSfs (medium sand); depth to the groundwater table obtained from LfU (2013). ”Additional instrumentation” indicates the availability of hydrometeorological or hydrological monitoring by the site owners (such as eddy flux towers, lysimeter, groundwater observation wells) in addition to the CRNS station itself.

ID	Location name	CRNS system	Land use	Soil texture	Depth to groundwater (m)	Additional instrumentation	Nearby rail track
BOO	Booßen	StyX S2	Cropland	Sl2	10	No	No
GOL	Golm	StyX S2	Grassland	fSms	2	No	Yes
PAU	Paulinenaue	StyX S2	Grassland	fSms	2	Yes	Yes
DED	Dedelow	StyX S2	Cropland	Sl2	10	Yes	No
KH	Kienhorst	StyX S2	Pine forest	mSfs	5-7.5	Yes	No
MQ[1]	Marquardt	CRS-1000	Cropland	Sl2	10-15	Yes	Yes
LIN	Lindenberg	CRS-2000	Grassland	Sl2	3	Yes	No
OEH[2]	Oehna	CRS-1000	Cropland	Sl2	10-15	No	No

[1] not part of the CRNS cluster described by Heistermann et al. (2023); [2] intermittent pivot irrigation in dry periods;

2.2 Retrieval and evaluation of soil moisture estimates from CRNS observations

Cosmic-Ray Neutron Sensing (CRNS) is based on the detection of neutrons generated by the interaction of cosmic radiation with Earth’s atmosphere. At ground level, the intensity of these neutrons is inversely related to the abundance of hydrogen in the near-surface environment (Desilets et al., 2010). While soil water typically constitutes the largest hydrogen pool, other occurrences of hydrogen may have to be accounted for (such as in vegetation, soil organic matter, or snow).

We estimate volumetric soil moisture from neutron intensities (θ_{CRNS}, $\mathrm{m}^3\,\mathrm{m}^{-3}$) according to a procedure referred to as ”general calibration” (Heistermann et al., 2024). In essence, the observed neutron intensities are converted to volumetric soil moisture by means of a non-linear transformation function (Desilets et al., 2010), using a uniform (”general”) value of 2306 cph for the calibration parameter N_0. In order to allow for the application of such a uniform N_0, the observed neutron intensities have to be standardised by accounting for a range of effects which we will only briefly summarize here (see Heistermann et al., 2024, for details):

- The **sensitivity of the neutron detector** relative to a known reference is required to standardize neutron count rates to a common level. To obtain the relative sensitivity, each sensor of the network was collocated to a sensor of known sensitivity for at least two days. The resulting relative sensitivity factors f_s are presented in Tab. 3 in section 3.1.
- The spatial variation of **incoming cosmic radiation** was accounted for by using the PARMA model (Sato, 2015) while the temporal variation was corrected for by using time series of the neutron monitor on the Jungfraujoch ("JUNG" in the neutron monitor database, https://www.nmdb.eu/nest).
- For eliminating the temporal **effects of barometric pressure and atmospheric humidity**, we used time series that were recorded locally at each CRNS station.
- **Soil organic carbon** (SOC) and **lattice water** (LW) content ($\mathrm{kg\,kg^{-1}}$) as well **soil dry bulk density** (ρ_b, $\mathrm{kg\,m^{-3}}$) in the sensor footprint were obtained during soil sampling campaigns: at a minimum of four locations within the sensor footprint, cylinder samples were extracted from the upper 30 cm of the soil at increments of 5 cm. For obtaining average values of these variables for the sensor footprint, we followed the weighting procedure outlined by Schrön et al. (2017).
- Heistermann et al. (2024) showed that the effect of **biomass** on the uncertainty of CRNS-based soil moisture estimates is negligible for grassland and cropland sites. For such sites (see Tab. 1), dry above-ground biomass (AGB) density was set to a constant value of $1\,\mathrm{kg\,m^{-2}}$. For the forest site (Kienhorst), the average dry AGB density was determined to a value of $11\,\mathrm{kg\,m^{-2}}$, based on allometric relationships together with extensive measurements of the breast height diameter of Pinus sylvestris at the Level II monitoring plots of the UNECE Convention on Long-range Transboundary Air Pollution (ICP Forests) to which the Kienhorst site belongs.

To evaluate the CRNS-based soil moisture estimates (θ_{CRNS}), reference observations within each CRNS footprint were obtained from the aforementioned soil sampling campaigns: Following Fersch et al. (2020), first, volumetric soil moisture was obtained for each of the four profiles sampled with cylinders; second, soil moisture profiles (30 cm depth, 5 cm increments) were measured by impedance-based soil moisture sensors (ThetaProbe ML2x, Delta-T Devices LLC, Cambridge, UK) at a minimum of 18 additional locations per footprint. The impedance-based measurements were calibrated to the collocated cylinder-based measurements. The cylinder- and impedance-based measurements were then averaged vertically and horizontally by using the weighting functions established by Schrön et al. (2017), resulting in an average value of θ_{REF} that is considered as the reference value representative for the CRNS footprint. This reference value will be used to assess the performance of the aforementioned estimation procedure.

2.3 Soil hydrological model set-up and evaluation

We employed the 1-dimensional Soil-Water-Atmosphere-Plant model (SWAP, van Dam et al., 2008) to simulate soil water dynamics and water fluxes at each monitoring location. SWAP calculates vertical soil water movement by solving the Richards equation, and hence accounts for infiltration and capillary rise on the basis of soil hydraulic properties and governing boundary conditions. Evapotranspiration is estimated using the Penman-Monteith equation, considering factors such as soil moisture content, vegetation type, and atmospheric conditions. This dual focus on soil hydrology and atmospheric interactions allows for a detailed analysis of the surface water balance and the movement of water through the unsaturated zone towards or from the groundwater table which is, in our model setup, considered as static (see Tab. 1) and implemented as a Dirichlet boundary condition.

As atmospheric forcing, we used daily climate observations of the German Meteorological Service (Deutscher Wetterdienst, DWD henceforth) at the nearest climate station (Fig. 1) for the following daily variables: minimum and maximum air temperature (°C), average relative air humidity (%), sunshine hours (h), and average wind speed ($\mathrm{m\,s^{-1}}$). For precipitation, we applied DWD's radar-based quantitative precipitation product RADOLAN (DWD, 2022) in order to better capture small-scale convective rainfall at the monitoring locations especially during the summer season. Tab. 2 highlights important vegetation-related model parameters that were used for our study, including the corresponding literature references.

Table 2. Overview of key SWAP model parameters related to vegetation and corresponding references.

Parameter name	Meaning	Forest	Grass/cropland	References
Leaves and roots				
GCTB	Max. leaf area index, LAI (-)	3.5	3.0	LFB (2025), Kroes et al. (2017)
RDTB	Rooting depth (cm)	150	40	Guerrero-Ramírez et al. (2021)
Evapotranspiration				
RSC	Minimum canopy resistance (s/m)	180	130	Guan and Wilson (2009)
Interception acc. to...				
...Von Hoyningen-Huene (1983)				
COFAB	Interception coefficient (cm)	–	0.25	Kroes et al. (2017)
...Gash et al. (1995)				
PFREE	Free throughfall coefficient (–)	0.32	-	Russ et al. (2016)
PSTEM	Stem flow coefficient (–)	0.02	–	
SCANOPY	Storage capacity of canopy (cm)	0.08	-	
AVPREC	Avg. rainfall intensity (cm/d)	3.30	–	
AVEVAP	Avg. evaporation int. during rain (cm/d)	0.46	–	

Finally, soil hydraulic parameters (SHP) need to be set in order to represent the relationship between matric potential (ψ, hPa) and volumetric soil water content (SWC, $\mathrm{m^3/m^3}$) as well as hydraulic conductivity (K_s, $\mathrm{cm\,d^{-1}}$). Using to the model of van Genuchten and Mualem (van Genuchten, 1980), the SHP correspond to five parameters: residual water content (θ_r, $\mathrm{m^3\,m^{-3}}$), saturated water content (θ_s, $\mathrm{m^3\,m^{-3}}$), air entry point (α, $\mathrm{cm^{-1}}$), and the shape parameter of the retention curve (n, dimensionless). To obtain SHP values at the monitoring locations, we applied the widely used pedotansfer function ROSETTA (Schaap et al., 2001). As input, ROSETTA requires the fractions of sand, silt and clay, which we obtained from the texture attribute of the state's soil map BUEK300 (LBGR, 2024, see also Tab. 1). This soil map, however, only represents a qualitative soil texture class which, in turn, implies typical ranges of sand, silt and clay content according to BGR (2005). In order to set specific values *within these ranges* at each monitoring location, we fixed the clay content T to a value of 5 percent and then adjusted the sand content S to a value that maximises the agreement between simulated soil moisture θ_{SWAP} and CRNS-based soil moisture θ_{CRNS}. The silt content U then results as the remainder 100% - S - T. This procedure could be framed as a "fine-tuning" of the sand content for a given soil texture class, ensuring SHP sets consistent with the soil map. The resulting model performance was evaluated based on the Nash-Sutcliffe-Efficiency (NSE), the mean absolute error (MAE) and the percent bias (PBIAS, i.e. the mean error relative to the observed mean), based on the comparison between simulated soil moisture and CRNS-based soil moisture. To allow for that comparison, the simulated vertical soil moisture profile (at cm-resolution down to a depth of 50 cm) at each daily time step was vertically weighted using the weighting function introduced by Schrön et al. (2017).

3 Results and discussion

3.1 CRNS-based soil moisture estimation

As pointed out in section 2.2, we applied the so-called general calibration function (Heistermann et al., 2024) in order to estimate the volumetric soil water content θ_{CRNS} from observed neutron count rates. The main motivation behind this approach is to avoid point measurements of SWC as a source of uncertainty for the local calibration of the conversion function. To apply the general calibration function, however, we require the sensitivity of the neutron detector relative to a reference detector (f_s), and several site-specific variables such as the gravimetric soil water equivalents of soil organic carbon and lattice water (θ^g_{SOM} and θ^g_{LW}), dry AGB density, and soil dry bulk density (ρ_b). Based on the data collection outlined in section 2.2, Tab. 3 reports the site specific values of these parameters, as well as θ_{REF} obtained from manual sampling at the date of the sampling campaign, and the corresponding value of θ_{CRNS}.

As we are not using θ_{REF} for local calibration, we can use it to assess the validity of the general calibration procedure, albeit being aware that θ_{REF} is also subject to considerable uncertainty. Overall, the absolute difference between θ_{CRNS} and θ_{REF} is always lower than $0.05\,\mathrm{m}^3\,\mathrm{m}^{-3}$. The mean absolute error (MAE) amounts to $0.034\,\mathrm{m}^3\,\mathrm{m}^{-3}$ which is, in our view, a good agreement given the absence of any local calibration. The mean error (ME) of $-0.025\ \mathrm{m}^3\,\mathrm{m}^{-3}$, however, indicates that a large portion of the MAE is due to a systematic underestimation of the soil moisture by θ_{CRNS}. This result is in line with some recent studies, including Heistermann et al. (2024), which suggest the use of a new type of conversion function recently published by Köhli et al. (2021). The original functional form suggested by Desilets et al. (2010) and also adopted by Heistermann et al. (2024) tends to underestimate soil moisture under dry conditions (as typical for Brandenburg). For future applications, we hence recommend to systematically assess the function from Köhli et al. (2021) for CRNS-based soil moisture estimation in Brandenburg.

Table 3. Parameters for CRNS-based SWC estimation (see main text), θ_{CRNS} and θ_{REF} at the sampling dates and the corresponding difference $\theta_{\mathrm{CRNS}} - \theta_{\mathrm{REF}}$ between these values.

ID	f_s^{-1} (–)	$\theta^g_{SOM} + \theta^g_{LW}$ (kg/kg)	ρ_b (kg m^{-3})	Sampling date	θ_{CRNS} (m^3 m^{-3})	θ_{REF} (m^3 m^{-3})	$\theta_{\mathrm{CRNS}} - \theta_{\mathrm{REF}}$ (m^3 m^{-3})
BOO	1.20	0.016	1420	2024-09-04	0.020	0.069	−0.049
GOL	1.13	0.045	1080	2024-09-03	0.084	0.120	−0.036
PAU	1.15	0.060	1510	2024-09-19	0.142	0.190	−0.048
DED	1.06	0.018	1470	2024-10-16	0.155	0.200	−0.045
KH	1.13	0.017	1030	2024-09-18	0.050	0.076	−0.026
MQ	0.49	0.015	1280	2023-05-17	0.132	0.097	0.035
LIN	0.87	0.014	1430	2021-11-19	0.165	0.199	−0.034
OEH	0.45	0.009	1500	2024-04-05	0.149	0.148	0.001
							MAE = 0.034
							ME = −0.025

3.2 Model evaluation

According to the state's soil map (LBGR, 2024), each of the eight monitoring locations belongs to one of the following three soil texture classes (see Tab. 1): slightly loamy sand (class Sl2), medium sand with parts of fine sand (mSfs), and fine sand with parts of medium sand (fSms). In section 2.3, we elaborated how soil hydraulic parameters (SHP) were obtained from these texture classes for each monitoring location. Tab. 4 summarizes the results of this procedure, including the corresponding model performance metrics.

According to the NSE and Moriasi et al. (2015), the model performance is satisfactory (NSE > 0.5) for six locations and good (NSE > 0.7) for two locations. The NSE amounts to a value of 0.77 (very good) if computed for all locations together which indicates that the model is able to capture the variability between the monitoring locations well. The MAE is relatively low (around 0.02 m^3 m^{-3}), and the percent bias (PBIAS) is low to moderate with a slight tendency towards an underestimation (strongest underestimation with -14.4 % at the the Booßen location)..

Fig. 2 shows the resulting CRNS-based (θ_{CRNS}) and simulated (θ_{SIM}) time series of SWC. In accordance with the performance metrics in Tab. 4, the seasonal and event dynamics are captured fairly well by the model. For the rare snow episodes since early 2024, the CRNS-based soil moisture estimate should not be interpreted (periods highlighted by light red shading). Apart from the general agreement, various discrepancies also highlight the need for improvements in the model and possibly also in the CRNS-based SWC estimation. Given the results from the previous section 3.1, we know that the way we calculated θ_{CRNS} tends to systematically underestimate the SWC. This puts the disagreement between θ_{SIM} and θ_{CRNS} for very dry conditions into perspective (see e.g. Booßen, Lindenberg, Marquardt and Oehna). For the locations Golm, Paulinenaue and Lindenberg (all of them grassland sites), there is a period from early October to mid November during which θ_{CRNS} becomes much lower

Table 4. The column block "Soil texture" documents the ranges of sand, silt and clay contents for the soil texture classes Sl2, mSfs, and fSms (BGR, 2005), and the adjusted sand, silt and clay contents as obtained by fine-tuning the sand content. The column block "SHP" quantifies the resulting values for the soil-hydraulic properties. The block "Metrics" shows the corresponding model performance metrics (NSE: Nash-Sutcliffe Efficiency, MAE: mean absolute error, PBIAS: percent bias).

ID	Soil texture		SHP					Metrics		
	class from soil map and S, U, T ranges (%)	S, U, T adjusted (%)	θ_r ($m^3\,m^{-3}$)	θ_s ($m^3\,m^{-3}$)	α (cm^{-1})	n (-)	K_s ($cm\,d^{-1}$)	NSE	MAE ($m^3\,m^{-3}$)	PBIAS (%)
BOO	Sl2: 67-85, 10-25, 5-8	75,20,5	0.05	0.38	0.022	1.6	77	0.52	0.033	−14.4
DED		82,13,5	0.05	0.37	0.025	1.7	120	0.56	0.021	−3.4
MQ		83,12,5	0.05	0.37	0.026	1.8	135	0.73	0.020	8.0
LIN		75,20,5	0.05	0.38	0.022	1.6	77	0.70	0.027	−2.1
OEH		85,10,5	0.05	0.37	0.027	1.9	167	0.60	0.017	7.5
KH	mSfs: 85-100, 0-10, 0-5	87,08,5	0.05	0.37	0.028	2.0	211	0.55	0.014	0.5
GOL	fSms: 65-75, 20-35, 0-5	75,20,5	0.05	0.38	0.022	1.6	77	0.51	0.033	2.4
PAU		66,29,5	0.05	0.39	0.017	1.5	59	0.51	0.034	−4.0
							all	**0.77**	**0.024**	**−1.2**

than θ_{SIM} which might indicate that the parameterisation of the late season vegetation dynamics and hence evapotranspiration are not adequately represented.

At this point, we should reiterate that the focus of this paper is to introduce the new soil moisture monitoring network in Brandenburg. The modelling analysis merely serves the purpose to demonstrate, on a case study basis, how a hydrological model could be used to increase the value of our CRNS-based soil moisture observations. Based on the above evaluation, we maintain that the model is able to reproduce the observed soil moisture dynamics in the upper 30–50 cm of the soil at a satisfactory to good level after model parameters were derived from literature values (vegetation) and the state's soil map (soil texture), with only a minimum level of calibration (fine-tuning of sand content within the ranges specified by local soil texture). The model hence can serve the purpose of being applied in a case study, as presented in the subsequent section, in order to support the analysis of soil water dynamics at the monitoring locations beyond the inherently limited scope of the observations.

3.3 Extending the scope of soil moisture observations by hydrological modelling

In the long term, the CRNS-based soil moisture monitoring could provide new insights into terrestrial water storage and drought conditions – simply because soil moisture has not yet been systematically monitored in Brandenburg at this level of horizontal and vertical representativeness. Still, the instrumental monitoring is inherently limited with regard to temporal and spatial coverage as well as concerning the actually observed variable. In the following, we will discuss how a soil hydrological model such as the one presented above might help to mitigate some of these limitations.

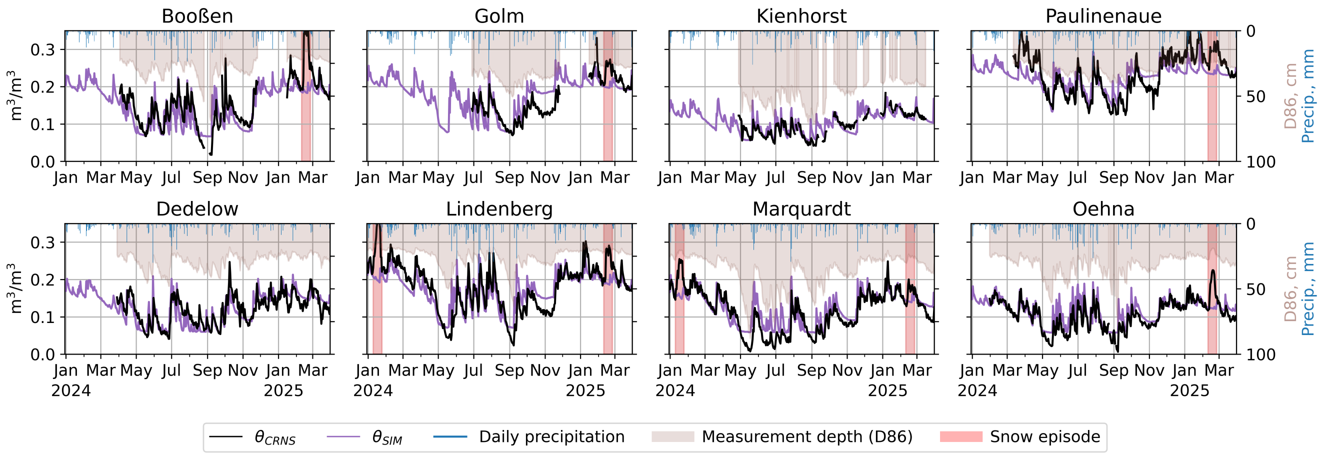

Figure 2. Observed (black) and simulated (purple) soil water dynamics at the monitoring locations, as well as CRNS measurement depth (D86, i.e. the depth that accounts for 86 % of the signal) and daily precipitation depths. Extended snow episodes are marked by the blue shade. During these times, the CRNS signal should not be interpreted in terms of soil moisture.

Increasing spatial coverage

It is possible to fully cover landscape parcels of up to 1 km^2 with CRNS sensors (see, e.g., Fersch et al., 2020; Heistermann et al., 2022, 2023). It is impossible, though, to scale this approach to a federal state such as Brandenburg with an area of almost 30,000 km^2. At that scale, any instrumental soil monitoring network will necessarily remain sparse. Model input data such as soil texture, land use, depth to groundwater, and hydro-meteorological forcing are, however, available at a much higher coverage (in terms of underlying sampling points and their spatial representativeness). Given the satisfactory to good model performance for the first, rather simplistic model parametrization (NSE of 0.77 when evaluating all locations together, see section 3.2), the prospects for model-based upscaling are tangible (although still limited to environmental conditions for which the model has been evaluated in the context of the present monitoring network). As a first upscaling application, Francke and Heistermann (2025) already used the model to assess the impact of climate change on groundwater recharge for five catchments across the state of Brandenburg. Undoubtedly, any model-based upscaling will also benefit from additional monitoring locations that supplement or extend the diversity of site characteristics currently covered by the network (see also section 4).

Increasing temporal coverage

Some locations exhibit considerable data gaps in terms of neutron time series (see specifically Booßen, Golm, and Kienhorst), which are caused, e.g., by shortages in solar power supply, sensor failures, or disruptions of remote data transmission. These gaps can be bridged by the hydrological model (see Fig. 2). Yet, the more significant type of gap arises from the fact that obviously no observations are available before the installation of the sensors. Here, the model can be particularly helpful to put current dynamics or specific years in context with the statistical properties of longer historical periods. For instance, Figs. 3

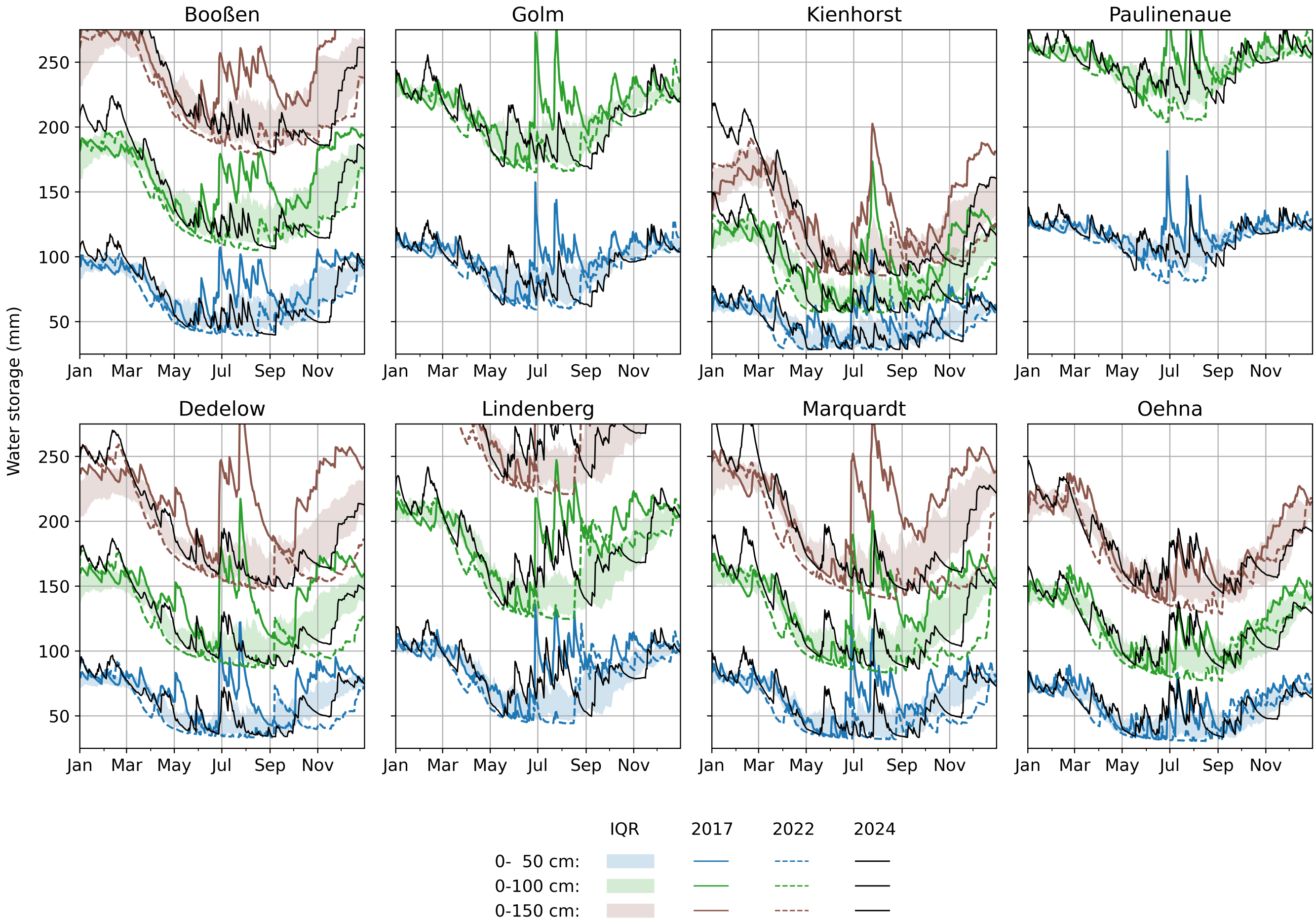

Figure 3. Model-derived soil water storage (in mm) for different integration depths (0-50 cm, 0-100 cm, 0-150 cm). The coloured shaded areas show the interquartile range of soil water storage for the 30 year period 1994-2023. The solid lines show the seasonal dynamics for the year 2017 (very wet), the dashed lines for the year 2022 (very dry), the black solid line for year 2024. Note that storage for the upper 150 cm is not fully shown for some locations (Golm, Paulinenaue, Lindenberg) because we used a uniform y-axis scaling (to allow comparability) while limiting the y-axis range to allow for better distinguishing temporal dynamics at different depths.

and 4 (see the next two paragraphs) contrast one very dry and one very wet year (2017 and 2022, respectively) as well as the first monitoring year (2024) with the typical seasonal dynamics of soil water storage and groundwater recharge between 1994 and 2023.

Enhancing information along the vertical dimension

θ_{CRNS} provides a depth-integrated estimate of soil moisture. The measurement depth is dynamic (see Fig. 2) as it depends itself on soil moisture. Some applications, however, would not only require integration depths other than the one provided by the

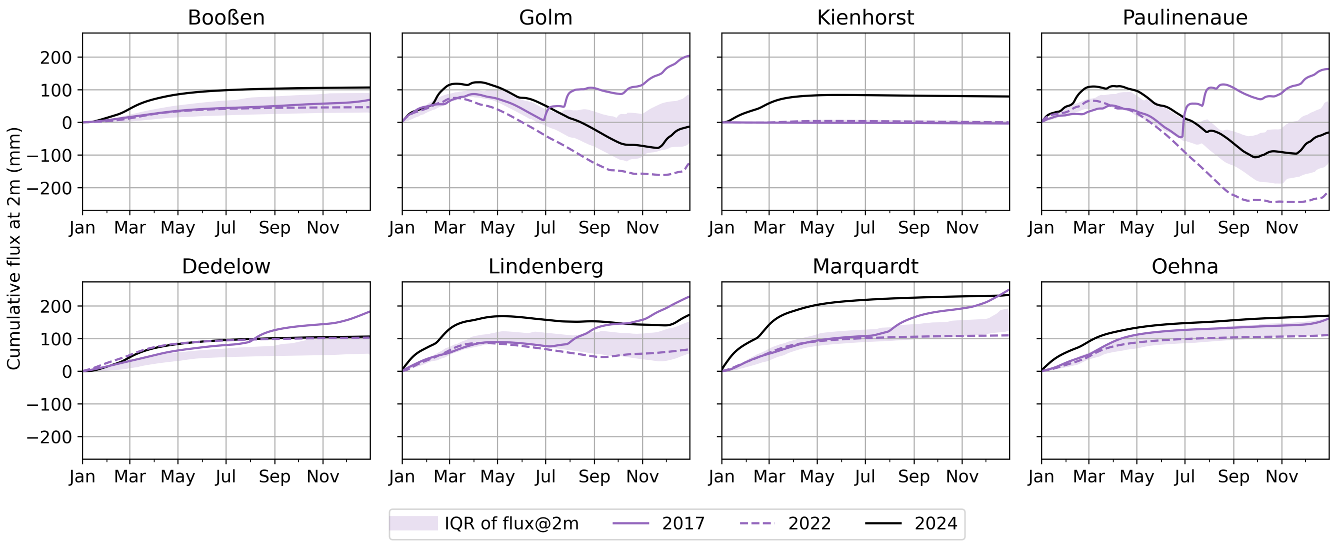

Figure 4. Modelled cumulative net flux across a soil depth of 2 m, as a proxy for groundwater recharge. Positive values indicate a net flux towards the groundwater table while negative value indicate a flux in the opposite direction, i.e. towards the soil surface. The purple shades shows the interquartile range of the annual cumulative flux in the period from 1994 to 2023. The lines show selected years (2017: wet year, 2022: dry year, 2024: first monitoring year).

CRNS sensor, but also integration depths that are, for the sake of comparability, invariant across time. Both could be provided by a hydrological model that is able to sufficiently resolve the vertical soil moisture dynamics. Fig. 3 demonstrates how the model could be used to quantify soil water storage for different integration depths (0-50 cm, 0-100 cm, and 0-150 cm) and, at the same time, to extend such information to time periods in which the sensor network had not yet been established (see previous paragraph). While we cannot appreciate the figure in full detail in the scope of this paper, we can maintain that the water storage varies considerably in space (between locations) and time (between seasons and years). The highest contrast in storage is between the Kienhorst location (pine forest on middle sand with a deep groundwater table) and the locations Golm and Paulinenaue (grassland on very fine sand with a shallow groundwater table). There is also a strong variability across Brandenburg in the development of soil water storage in the very wet year 2017 and the very dry year 2022: for the Oehna location, both years were rather average, while the contrast between 2017 and 2022 is specifically distinct for the locations Dedelow and Marquardt. This demonstrates the need to account for both spatial and temporal variability. The example of the year 2022 also shows how the persistence of water deficits depends on integration depth: at the locations Dedelow and Marquardt, the upper 50 cm of the soil already recover to average conditions at the end of the year 2022 while the storage in the upper 100 and 150 cm are still within the lowest quartile. Conversely, at the Lindenberg location, the 2022 drought already ended in August after a series of heavy rainfall events.

Reconstruction of water fluxes

For water resources management, water fluxes (such as groundwater recharge), are often even more relevant than soil water storage. Fig. 4 shows the modelled cumulative net water flux across a soil depth of 2 m. This variable is typically used as a proxy for groundwater recharge, so we will refer to it as GWR in the following. As before, the figure contrasts the typical behaviour from 1994-2023 (in terms of the interquartile range) with three selected years (2017 as a wet year, 2022 as a dry year, and 2024 as the first monitoring year). While a comprehensive discussion of the figure is beyond the scope of this article, we can confirm a strong variability of GWR across time (years) and space (locations). For most locations, 2024 features an exceptional level of GWR which is, to a large extent, the consequence of an extraordinarily wet December 2023. The peculiarity of the year 2024 becomes specifically obvious in the Kienhorst location, a dry pine forest for which annual GWR is typically close to zero. In locations with a close groundwater table (most notably in Golm and Paulinenaue, less pronounced in Lindenberg), the seasonal dynamics of GWR are very different from those locations with a deep groundwater table. This is caused by an upward flux from the groundwater table to the root zone during the summer, even causing a negative cumulative water balance in some years (most clearly in 2022). The figure again highlights that the summer of 2017 was remarkable as it featured a positive net flux across the 2 m depth for many locations (Golm, Paulinenaue, Dedelow, Lindenberg, Marquardt) - a process that is typically limited to the winter season. Altogether, it should be maintained that due to the low storage capacity of soils in Brandenburg, precipitation anomalies tend to affect vertical fluxes stronger than soil water storage, and that temporal dynamics of soil water storage do not allow for any direct inference of vertical fluxes.

3.4 Lessons learned from the first year of operation

Apart from the aforementioned theoretical findings (sections 3.1-3.3), the first year of network operation also brought some practical and organisational experiences which we would like to share in brief.

- Working together with state government agencies from the very beginning helped to align the outcome of the monitoring effort with the requirements of the actual users, starting from the selection of monitoring locations (see also section 2.1) and not ending with the development and presentation of monitoring products. This co-design approach should also help to make the effort more sustainable, anchoring it in institutional structures that are more long-lived than research contexts, and also taking advantage of synergies with existing monitoring infrastructures.
- Collocating the CRNS sensors with a neutron detector of known sensitivity *before* the sensors are installed in the field helps to detect, track and understand any later changes in sensitivity (e.g. from drift or firmware updates, see next points).
- As with any sensor operated under outdoor conditions, CRNS instruments are prone to a range of issues, such as, e.g., failures of remote data transmission in areas with poor network coverage, failures or limitations in solar power supply for specific environments (namely forests) or seasons (namely winter), or sensor drift and instability. For the timely detection of any of these issues, it was vital to set up, from the beginning, a routine near-real time data retrieval and processing workflow, including a visualisation that allows for an intuitive detection of gaps or inhomogeneities. Specifically for

CRNS sensors, this includes an early implementation of soil moisture retrieval since implausible records become more obvious for a rather intuitive variable such as soil moisture in comparison to a more complex variable such as neutron intensity.

- In the same vein, it is helpful to implement and operate a soil hydrological model for the monitoring locations as early as possible. This does not only provide an added value from the scientific perspective (as outlined in section 3.3), but also allows for the detection of more subtle sensor issues. For instance, in the context of a series of firmware updates for some of the sensors, the comparison to the routine model output allowed for a timely detection of changes in sensor sensitivity which propagated to the soil moisture estimates in a substantial, but less obvious way.

- Given the previous two items, we set up a platform for visualising and sharing both observational and simulated data (https://cosmic-sense.github.io/brandenburg) with relatively short latency. The platform is under continuous development, specifically with regard to data presentation formats, and open to suggestions by interested users.

4 Conclusions and outlook

In this study, we introduced a new network for long-term soil moisture and drought monitoring in Brandenburg, using cosmic-ray neutron sensing (CRNS) technology. The launch of this network in 2024 resulted from a joint effort of research institutions and state government agencies that is, so far, unique in Germany. In 2024, eight locations were instrumented, and four more ware about to follow in 2025.

We consider the monitoring network as an important asset to support the management of water-related risks in Brandenburg, as it represents the unique regional characteristics in terms of climate, soils, land use, and distance to the groundwater table. We also demonstrated that the value of the observational data can be enhanced by a soil hydrological model, allowing for an increase in temporal, horizontal and vertical coverage as well as for the reconstruction of vertical water fluxes. We would like to emphasize, though, that the combination of model and data is only one way to make use of this observational network, and that our model application should be seen as a case study rather than any final analysis, which would benefit from longer collected time series and more sophisticated model adjustments. In order to stimulate future applications in various related fields, and to allow for any interested parties to use the data according to their priorities, we openly share the observational and the simulated data on a public platform (see section ”Data availability”), and invite collaboration in the improvement, enhancement, and integration of our network. That way, various opportunities arise, which could include, but are not limited to:

- **Improving soil moisture retrieval from CRNS**: in close collaboration with the sensor manufacturers, the long-term operation of CRNS sensors should help us to identify, understand and fix sensor issues that are, e.g., related to signal stability and traceability. Furthermore, there is a considerable potential to further improve the CRNS-based soil moisture estimation. For the relatively dry conditions in Brandenburg, a new conversion function recently suggested by Köhli et al. (2021) appears particularly promising. To that end, it would be desirable to combine this function with attempts to generalize the estimation of soil moisture from neutron intensities (Heistermann et al., 2024).

– **User-oriented monitoring products**: The integration of model and observation should allow to custom-tailor data products to specific user requirements. For instance, different vertical integration depths or temporal aggregation levels of soil water storage might be relevant in the context of wild fire hazards, agricultural management (e.g., timing of field operations, including irrigation), water resources management, or flood hazards (e.g., capacity for soil water retention, although flood generation is not a primary concern in Brandenburg). The design of such products should be subject to a continuous dialogue with potential users in the aforementioned sectors, including the involved federal state agencies, but also, e.g., farming or forestry companies.

– **Groundwater recharge**: Similarly, combining model and observational data should enable more accurate estimates of groundwater recharge rates under different conditions, including scenario analysis of land use and climate change.

– **Upscaling and transferability**: the results of our model evaluation (section 3.2) suggested the model to be transferable to locations that are similar in terms of climate, soil, land use and groundwater table depth. In addition to model-based upscaling, there are other promising opportunities for integrating soil moisture observations across larger spatial scales. While previous efforts focused on remote sensing, an emerging perspective for future research is rail-borne CRNS roving: several locomotives of a regional rail company have recently been equipped with CRNS sensors in order to monitor spatio-temporal soil moisture patterns along selected railway tracks (see Fig. 1). While those of our monitoring locations which are close to these railway tracks (Tab. 1) could be used to verify the spatiotemporal integrity of the railborne data products, the latter could, in turn, be used to validate or train other model-based or data-driven upscaling approaches.

– **Network extension**: it is planned to expand the network in Brandenburg, and we encourage other institutions to integrate their sensors or to propose suitable locations for deployment. Similar efforts are underway in other federal states, e.g., Saxony (Schrön et al., 2025). Collaboration and integration with these initiatives could be a pathway towards a prospective nation-wide monitoring.

In any case, the CRNS-based soil moisture monitoring network is intended as a long-term activity, and will also increase its value as the length of the observational time series increases and hence covers a higher diversity of hydro-climatological conditions.

Data availability. Raw CRNS observations, CRNS-based soil moisture estimates, and simulated soil water content are openly available for download at https://cosmic-sense.github.io/brandenburg.

Author contributions. DA, AB, AM, and SO designed and established the CRNS monitoring network, with contributions from all co-authors. MH carried out the data analysis and modelling, created the figures and drafted the manuscript, with support from TF. All co-authors contributed to writing and reviewing the manuscript.

Competing interests. The contact author has declared that neither they nor their co-authors have any competing interests.

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