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COSMOS-UK: National soil moisture and hydrometeorology data for empowering UK environmental science

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Abstract. The COSMOS-UK observation network has been providing field scale soil moisture and hydrometeorological measurements across the UK since 2013. At the time of publication a total of 51 COSMOS-UK sites have been established, each delivering high temporal resolution data in near-real time. Each site utilises a cosmic-ray neutron sensor, which counts fast neutrons at the land surface. These measurements are used to derive field scale near-surface soil water content, which can provide unique insight for science, industry, and agriculture by filling a scale gap between localised point soil moisture and large-scale satellite soil moisture datasets. Additional soil physics and meteorological measurements are made by the COSMOS-UK network including precipitation, air temperature, relative humidity, barometric pressure, soil heat flux, wind speed and direction, and components of incoming and outgoing radiation. These near-real time observational data can be used to improve the performance of hydrological models, validate remote sensing products, improve hydro-meteorological forecasting and underpin applications across a range of other scientific fields. The most recent version of the COSMOS-UK dataset is publically available at https://doi.org/10.5285/37702a54-b7a4-40ff-b62e-d14b161b69ca (Stanley et al., 2020).

1 Introduction

Soil moisture plays a crucial role in a range of biogeophysical and biogeochemical land surface processes (Moene and van Dam, 2014). These processes include the transport of energy and matter via evapotranspiration, drainage, run-off, infiltration and plant photosynthesis. Since 2013 the UK Centre for Ecology & Hydrology (UKCEH) has established the world's most spatially dense national network of innovative cosmic-ray neutron sensors (CRNS) to monitor soil moisture across the UK. The Cosmic-ray Soil Moisture Observing System for the UK (COSMOS-UK) delivers field scale near-surface soil water content for around 50 sites in near-real time (https:\\cosmos.ceh.ac.uk). The measurement footprint of these soil moisture observations, collocated with hydrometeorological measurements, is directly relevant to Land Surface Models (LSMs) and Earth Observation (EO) data products. COSMOS-UK therefore aims to transform hydrological and land surface modelling and monitoring, enabling and supporting a range of applications across science and industry.

Whilst the UK has a long history and well-established tradition of monitoring meteorological and hydrometeorological variables, namely precipitation, temperature and river flow, soil moisture has until recently been difficult to measure in a cost effective way and at a scale appropriate to many applications. Real-time soil moisture information is crucial in understanding the susceptibility of rainfall to cause flooding, the need for irrigation, the likelihood of landslip, and the suitability of undertaking agricultural activities. Additionally, knowledge of the soil moisture regime informs all land-use planning, the need for drainage, water resource development, flood forecasting, drought management, and agricultural development. With the absence of appropriate sensor technology, most notably due to the gap in spatial scale between small-area sensors and large-area remote sensing, soil moisture information has needed to be estimated by hydrological and land-surface models. The

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development and use of the CRNS provides appropriate scale data to enable model application, calibration and testing as well as providing near-real time data of local relevance.

COSMOS-UK fills a critical gap in UK hydrological monitoring by utilising CRNS to monitor field scale soil moisture (see the UK Water Resources Portal, https://eip.ceh.ac.uk/hydrology/water-resources/). At each COSMOS-UK site the CRNS sits above ground, autonomously counting fast neutrons for near-real time processing at UKCEH. The instrument has a measurement footprint of approximately 12 hectares, and can measure to a depth of approximately 80cm depending on local conditions (see Sect. 3.1 for details). This therefore fills the scale gap between buried point soil sensor measurements and very near surface soil data captured in EO soil moisture products. CRNS data are being used across the globe, including from networks in the United States (Zreda et al., 2012), Australia (Hawdon et al., 2014), Germany (Baatz et al., 2014; Fersch et al., 2020), Kenya and India (Montzka et al., 2017). COSMOS-UK aims to support science, industry and agriculture by providing reliable, accurate and timely soil moisture information for the UK.

This paper introduces the COSMOS-UK network and the data available for use. Current instrumentation and protocols are described in Sect. 2. Section 3 outlines how the data are handled. Section 4 describes the datasets that are available for download from The Environmental Information Data Centre (EIDC) online data repository. A selection of existing and potential data applications are discussed in Sect. 5, followed by conclusions.

2 Measurement methodology

2.1 Network creation

Between 2013 and the time of writing, UKCEH has deployed 51 COSMOS-UK environmental monitoring sites across the UK (Fig. 1) (Boorman et al., 2020). Two sites, Wytham Woods and Redmere, have been decommissioned during this time due to changes to site conditions and access. A summary of each site's main characteristics is included in Table 1, and a record of any changes to site land cover is provided in Table 2.

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Figure 1: Map of COSMOS-UK site locations (Boorman et al., 2020).

Table 1: Site information. Standard Average Annual Rainfall (SAAR) is provided by the Flood Estimation Handbook (FEH) catchment descriptor SAAR6190 as described in Bayliss (1999).

Site name	Start date	End date	Easting	Northing	Soil type	Altitude (m)	SAAR (mm)	Current land cover
Alice Holt	06/03/2015		479950	139985	Mineral soil	80	801	Broadleaf woodland
Balruddery	15/05/2014		331643	732797	Mineral soil	130	740	Arable and horticulture

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Bickley Hall	28/01/2015	353112	347903	Mineral soil	78	727	Grassland
Bunny Park	27/01/2015	458884	329606	Mineral soil	39	579	Arable and horticulture
Cardington	24/06/2015	507991	246422	Mineral soil	29	552	Improved grassland
Chimney Meadows	02/10/2013	436113	201160	Calcareous mineral soil	65	1740	Acid grassland
Chobham Common	24/02/2015	497737	164137	Organic soil over mineral soil	47	626	Heather grassland
Cochno	23/08/2017	249980	674651	Mineral soil	168	662	Improved grassland
Cockle Park	21/11/2014	419544	591351	Mineral soil	87	1387	Arable and horticulture
Crichton	02/12/2014	298903	573164	Mineral soil	42	720	Arable and horticulture
Cwm Garw	29/06/2016	211350	231661	Mineral soil	299	1051	Improved grassland
Easter Bush	13/08/2014	324557	664463	Mineral soil	208	798	Improved grassland
Elmsett	11/08/2016	605122	248260	Calcareous mineral soil	76	564	Arable and horticulture
Euston	31/03/2016	589619	279776	Mineral soil	18	600	Improved grassland
Fincham	07/06/2017	570068	305182	Calcareous mineral soil	15	613	Arable and horticulture
Fivemiletown	26/06/2018	55851	502136	Mineral soil	174	1227	Arable and horticulture
Gisburn Forest	15/08/2014	374899	458714	Mineral soil	246	1485	Coniferous woodland
Glensaugh	14/05/2014	365870	780483	Organic soil	399	1109	Heather
Glenwherry	15/06/2016	142962	556604	Organic soil	274	1340	Improved grassland
Hadlow	27/10/2016	562097	150263	Mineral soil	33	669	Improved grassland
Hartwood Home	20/05/2014	285476	658957	Mineral soil	225	946	Improved grassland
Harwood Forest	22/05/2015	398505	591355	Organic soil	300	895	Coniferous forest
Henfaes Farm	17/12/2015	265750	371709	Mineral soil	287	1282	Acid grassland
Heytesbury	16/08/2017	394535	144856	Calcareous mineral soil	166	909	Improved grassland
Hillsborough	14/06/2016	136345	513358	Mineral soil	146	674	Improved grassland

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Hollin Hill	25/03/2014		468121	468811	Mineral soil	82	673	Improved grassland
Holme Lacy	11/04/2018		354663	236036	Mineral soil	76	832	Arable and horticulture
Loddington	26/04/2016		479565	302022	Mineral soil	186	1084	Arable and horticulture
Lullington Heath	16/12/2014		554365	101634	Calcareous mineral soil	119	664	Heather grassland
Moor House	04/12/2014		369920	529470	Mineral soil	565	825	Heather grassland
Moreton Morrell	15/11/2018		429959	255776	Mineral soil	53	1239	Acid grassland
Morley	14/05/2014		605826	298803	Mineral soil	55	611	Arable and horticulture
North Wyke	16/10/2014		265707	98832	Mineral soil	181	620	Arable and horticulture
Plynlimon	05/11/2014		280322	285397	Organic soil	542	979	Improved grassland
Porton Down	18/12/2014		422406	135670	Calcareous mineral soil	146	2421	Acid grassland
Redhill	18/02/2016		569577	154326	Calcareous mineral soil	91	759	Orchard
Redmere	10/02/2015	20/09/2018	564639	285846	Organic soil	3	559	Arable and horticulture
Riseholme	04/05/2016		498425	374863	Calcareous mineral soil	53	656	Improved grassland
Rothamsted	25/07/2014		511887	214048	Mineral soil	131	603	Arable and horticulture
Sheepdrove	24/10/2013		436039	181395	Mineral soil	170	692	Arable and horticulture
Sourhope	19/11/2014		385562	620698	Mineral soil	487	737	Improved grassland
Spen Farm	23/11/2016		444887	441620	Calcareous mineral soil	57	1009	Arable and horticulture
Stiperstones	06/11/2014		336086	298579	Organic soil	432	654	Grassland
Stoughton	19/08/2015		464641	300854	Mineral soil	130	641	Arable and horticulture
Sydling	27/11/2018		362917	103337	Mineral soil	249	874	Acid grassland
Tadham Moor	14/10/2014		342199	145692	Organic soil	7	1064	Grassland
The Lizard	17/10/2014		170940	19648	Mineral soil	85	749	Grassland
Waddesdon	04/11/2013		472548	216176	Mineral soil	98	636	Improved grassland
Wimpole	10/09/2019		533951	250013	Mineral soil	30		Arable and horticulture

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Writtle	04/07/2017		567062	206687	Mineral soil	44	555	Improved grassland
Wytham Woods	26/11/2013	01/10/2016	445738	208942	Mineral soil	109	571	Broadleaf woodland

Table 2: Changes in land cover at COSMOS-UK sites.

Site ID	Land Cover	Land Cover Start Date
Crichton	Improved grassland	21/11/2014
	Arable and horticulture	10/05/2019
North Wyke	Improved grassland	16/10/2014
	Arable and horticulture	09/09/2019
Sheepdrove	Improved grassland	24/10/2013
	Arable and horticulture	03/10/2019

The selection of sites within the network has aimed to provide an appropriate spatial coverage for improving understanding of UK soil moisture conditions, including representation of key land cover and soil types. All UK regions are represented, though there are more sites in the south and east of the UK to adequately capture the greater soil moisture variability in these areas. Specific site locations have been further determined by practical considerations such as long-term permission and reasonable access for instrument installation and maintenance, and mobile phone network coverage. Where possible, site selection has aimed to exploit opportunities for COSMOS-UK data to support independent, existing research projects, e.g. data assimilation for forecasting and prediction; validation of remote sensing data; and support of other monitoring programmes and activities. Similarly, site selection has aimed to create partnerships with farmers and support agricultural research.
Some site characteristics can limit their suitability for CRNS soil moisture measurement, such as proximity to open water or shallow or perched groundwater (such features should not be present within the CRNS measurement footprint), and highly variable topography.

2.2 Site data acquisition

Instrumentation at COSMOS-UK sites is largely standardised (Fig. 2), however differences have arisen for the following reasons.

- When instrument performance was reviewed resulting in subsequent installations utilising different, higher-performance sensors (e.g. for improved sensor accuracy).
- Where a site has been located in an area which is expected to experience a significant period of snow cover, the monitoring equipment includes additional sensors for measurements of snow.

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- Where a site has been located within a forest and requires measurements from a tower structure above the canopy of mature vegetation.

These site differences are detailed in Table 3. For further information regarding individual instruments, a detailed summary is provided in the COSMOS-UK User Guide (Boorman et al., 2020).

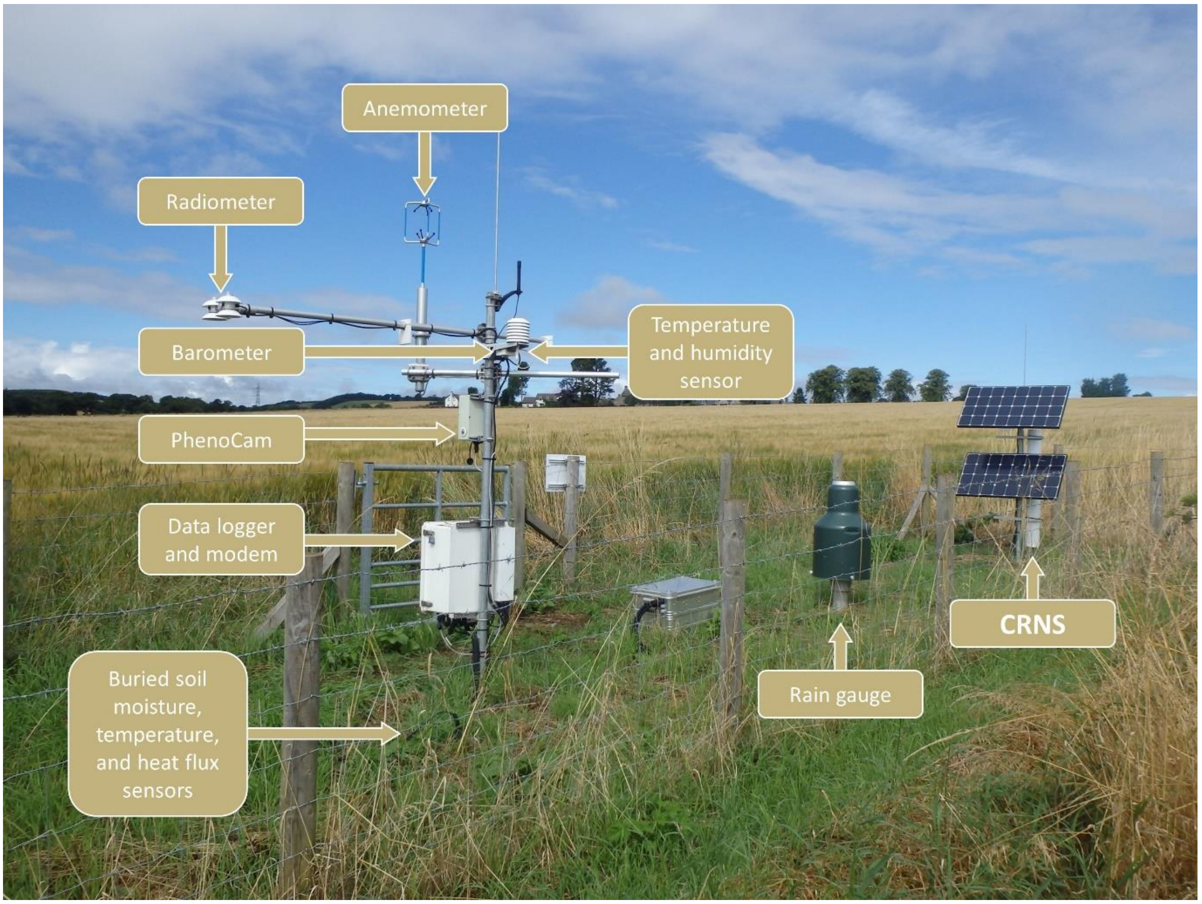

Figure 2: COSMOS-UK site instrument layout. Photograph of the Balruddery site in Scotland. Photograph taken by Jenna Thornton.

Table 3: COSMOS-UK site instrumentation. The snow depth SR50A sensors and SnowFox CRNS are only at sites established as sites experiencing significant periods of snow cover.

Data	Instrument		
Neutron counts and field scale soil moisture	Hydroinnova CRS1000/B CRNS	OR	Hydroinnova CRS2000/B CRNS
Point soil moisture and temperature	2 Acclima ACC-SEN-SDI (TDT)		

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Profile soil moisture and temperature	1 IMKO PICO-PROFILE and 1 Hukseflux STP01	OR	8 Acclima ACC-SEN-SDI (TDT) and 1 Hukseflux STP01
Point soil heat flux	2 Hukseflux HFP01SC		
Precipitation	1 OTT Pluvio^2(L)	OR	1 OTT Pluvio^2(L) and 1 SBS500
Short- and long-wave radiation in and out	Hukseflux NR01		
Air temperature and relative humidity	Rotronic HC2(A-)S3	OR	Vaisala HMP155(A)
Barometric pressure	Gill MetPak Pro Base Station	OR	Vaisala PTB110
Wind speed and direction	Gill Integrated WindSonic	OR	Gill WindMaster 3D Sonic Anemometer
PhenoCam photos	Mobotix S14 OR S15 OR S16 IP camera		
Snow depth	Campbell Scientific SR50A		
Neutron counts for snow water equivalent	Hydroinnova SnowFox CRNS		

Available measurements are described below, and further information regarding variables and recording intervals is provided in Sect. 4. All COSMOS-UK measurements are logged on a CR3000 Micrologger (Campbell Scientific Ltd., Logan, Utah, USA) and telemetered via the 2G, 3G or 4G mobile network, or Inmarsat BGAN satellite network (Inmarsat Global Ltd., London, UK), to secure servers at UKCEH Wallingford. Telemetry has been achieved using either a COM110 (Campbell Scientific Ltd., Logan, Utah, USA), Maestro M100 (Lantronix Inc., Irvine, California, USA), Proroute® H820 (E-Lins Group, Shenzhen, China), or 9502 BGAN (Hughes Network Systems LLC, Germantown, Maryland, USA) modem.

Sensor calibration coefficients are stored on the CR3000 for measurements such as soil heat flux (G, W m^{-2}) and the four components of net radiation (RN, W m^{-2}). Equipment across the network is promptly replaced when faults are detected, and instruments are tested and re-calibrated on an annual basis under a maintenance contract with the suppliers of the field instrumentation, Campbell Scientific Ltd. A full record of sensor exchanges is maintained by UKCEH.

2.2.1 Soil data

Each COSMOS-UK site utilises a moderated CRS2000/B CRNS (Hydroinnova LLC, Albuquerque, New Mexico, USA) which counts fast neutrons at the land surface. Some sites have previously utilised a bare and/or moderated CRS1000/B (Hydroinnova LLC, Albuquerque, New Mexico, USA) (Zreda et al., 2012). The neutron counts are used to derive average field scale volumetric water content (VWC, %) of the near-surface soil layer (see Sect. 3.1 for details). Each site includes either two (deployment prior to March 2016) or ten buried ACC-SEN-SDI point soil moisture sensors (TDTs) (Acclima Inc., Idaho, USA) to measure small-area soil VWC (%) at defined depths (listed in Table 4). Sites installed prior to March 2016 included a PICO-PROFILE soil moisture sensor (IMKO Micromodultechnik GmbH, Ettlingen, Germany) to measure VWC (%) at depths of 0.15, 0.4 and 0.65 m; these instruments were subsequently removed from sites during 2019-2020 network maintenance to improve overall performance. Soil heat flux (W m^{-2}) is measured at every site using a pair of HFP01-SC sensors (Hukseflux Thermal Sensors B.V., Delft, The Netherlands) buried at a depth of 0.03m. All sites include an STP01 profile soil temperature sensor (Hukseflux Thermal Sensors B.V., Delft, The Netherlands) to measure the soil temperature gradient (°C) at 0.02, 0.05, 0.1, 0.2 and 0.5 m depths.

Table 4: Buried depths of the Acclima TDT point soil sensors. TDT3-10 are only present at sites installed on or after 31 March 2016. At the Heytesbury site TDT9 and TDT10 are buried at 0.05 m depth due to the presence of solid chalk.

TDT1	TDT2	TDT3	TDT4	TDT5	TDT6	TDT7	TDT8	TDT9	TDT10
0.1m	0.1m	0.05m	0.05m	0.15m	0.15m	0.25m	0.25m	0.5m	0.5m

2.2.2 Hydrometeorological data

COSMOS-UK sites include a Pluvio^2(L) digital weighing rain gauge (OTT HydroMet, Kempten, Germany) installed with an aperture height of 1 m above the soil surface. These rain gauges measure precipitation intensity and amount (mm) at one minute resolution. Incoming and outgoing short- and long-wave radiation (W m^{-2}) are measured at each site using an NR01 four-component net radiometer (Hukseflux Thermal Sensors B.V., Delft, The Netherlands). Barometric pressure (hPa) is measured at all sites using either a Gill MetPak Pro Base Station (Gill Instruments Ltd., Lymington, UK) at a height of 2 m or a PTB110 barometer (Vaisala Corporation, Helsinki, Finland). From this, pressure corrected to sea level is derived. Air temperature (°C) and relative humidity (%) are measured at every site using either an HC2(A-)S3 (Rotronic, Bassersdorf, Switzerland) or HMP155(A) sensor (Vaisala Corporation, Helsinki, Finland). Air temperature and relative humidity are measured at the standard height of 2 m. Wind speed and direction are measured using either a 2-dimensional WindSonic at a measurement height of 2.2 m or 3-dimensional WindMaster anemometer (Gill Instruments Limited, Lymington, UK) at a measurement height of 2.6 m.

2.2.3 Non-standard sites

COSMOS-UK sites located in dense forest or woodland (Alice Holt, Harwood Forest and Wytham Woods) were designed with certain meteorological sensors installed above the canopy, on pre-existing flux monitoring towers. Wind measurements, barometric pressure, relative humidity, air temperature, precipitation, and the components of net radiation are measured above the canopy. The measurement height of these variables ranges from approximately 23–33 m. Precipitation is captured by a funnel above the canopy and fed via a tube to the Pluvio^2(L) rain gauge located at ground level. Forest sites do not accurately measure rainfall intensity due to the lag time in precipitation captured above canopy and recorded in the rain gauge below. Precipitation data are corrected for the smaller aperture area of the funnel relative to that of the Pluvio^2(L).

Across the COSMOS-UK network, eight site locations were identified in areas likely to experience a significant period of snow cover over the winter period. These sites were installed with two additional sensors: an SR50A snow depth sensor (Campbell Scientific Ltd., Logan, Utah, USA) measuring small area snow depth (mm); and a buried SnowFox CRNS (Hydroinnova LLC, Albuquerque, New Mexico, USA) measuring neutron counts which can be used to derive snow water equivalent (Desilets, 2017).

Tadham Moor is located on the Somerset Levels, an area that can experience inundation during high rainfall. The COSMOS-UK site was therefore adapted to withstand any significant floodwater. For this reason, the digital weighing rain gauge has an aperture height of approximately 1.7 m, and the CRNS is installed horizontally at a height of approximately 1.1 m rather than vertically. This non-standard installation enables an assessment of the CRNS technology in a very high soil moisture environment.

During COSMOS-UK network maintenance in February 2020 an SBS500 tipping bucket rain gauge (Environmental Measurements Limited, North Shields, UK) was added to three sites (Chimney Meadows, Sheepdrove and Waddesdon), providing an additional precipitation (mm) reference against which the performance of the Pluvio^2(L) rain gauges can be evaluated.

2.3 Soil sampling and lab analysis for site calibration

An in situ soil sampling procedure adapted from Franz (2012) and Zreda et al. (2012) has been completed at each COSMOS-UK site following installation. The results from the sampling are used to determine site-specific soil properties for CRNS calibration: field average soil moisture and dry bulk density, lattice and bound water, and organic matter. Once the CRNS count data have been corrected for atmospheric pressure (Desilets, 2017), humidity (Rosolem et al., 2013) and background neutron intensity (Desilets, 2017), the calibration data are used to derive N_0 on the day of calibration (details in Sect. 3.1). Soil samples for determination of VWC and dry bulk density are taken at 18 representative locations centred on the CRNS: at compass bearings of 0, 60, 120, 180, 240 and 300 degrees and at 5, 25 and 75 m radial distance at each of these compass bearings (Fig. 3). For CRNS calibrations before 14 September 2016, samples were taken at 25, 75 and 200 m radial distances. These locations follow Franz (2012), subsequently modified to account for revised CRNS footprint characteristics (Köhli et al., 2015). In addition, as the 180 degree sample at 5 m distance would fall on a cable run within the CRNS enclosure, this location has been replaced with a sample at either 90 or 270 degrees at 1 m distance. At each location volumetric soil samples (using 0.05 m diameter, 0.051 m length rings) are taken at five depths: 0–0.05, 0.05–0.1, 0.1–0.15, 0.15–0.2 and 0.2–0.25 m below ground level (bgl). Three locations at different bearings and distances were also selected for an additional soil sample for the determination of lattice and bound water and organic matter. The additional soil samples were taken from 0–0.25 m bgl. This therefore gives a total of 90(+3) soil samples for each calibration.

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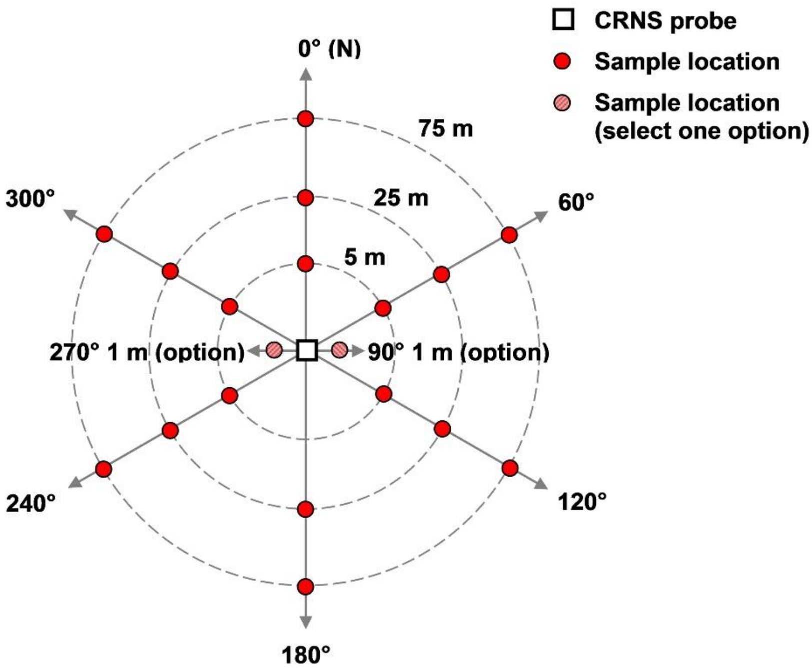

Figure 3: Plan view of soil sampling locations (not to scale).

The field soil samples were returned to the laboratory for analysis. VWC and dry bulk density were determined for the 90 volumetric samples using oven drying (~36 hours at 105 °C). Following analysis, a ~2 g sub-sample was taken from each sample and aggregated to form a composite sample for lattice and bound water and organic matter determination. The three additional soil samples from the field were air dried (on the lab bench or in the oven at 30 °C) for around three days. The additional samples, along with the composite, were then crushed to pass a ~0.4 mm sieve and subsequently air dried at 105 °C for ~36 hours. Soil organic matter was then estimated for a ~3 g air dried sub-sample (with 6 replicates per additional sample, i.e. 24 sub-samples) using loss on ignition at 400 °C for 16 hours in the furnace (following Nelson and Sommers, 1996). Following cooling in a desiccator and weighing, the sub-samples were then returned to the furnace to estimate lattice and bound water by loss on ignition at 1000 °C for 4 hours (following Pansu and Gautheyrou, 2006). For use in the CRNS calibration calculation, soil organic carbon was estimated as 50 % of soil organic matter (Nelson and Sommers, 1996). Pansu and Gautheyrou (2006) note that loss on ignition removes organic matter at 300–500 °C and lattice and bound water at 350–1000 °C. The procedure outlined above therefore follows the 400 °C temperature recommendation by Nelson and Sommers (1996), which removes organic matter but causes minimal dehydroxylation of clay minerals. The CRNS calibration procedure uses the mean soil organic carbon and mean lattice and bound water from the 24 sub-samples along with the mean dry bulk

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205 density from the 90 volumetric samples. The field average reference VWC for the day of calibration is then calculated as a radial and vertical weighted mean following Köhli et al. (2015).

Secondary samples have been collected at two COSMOS-UK sites to explore the accuracy of the derived VWC obtained on a particular day using this methodology. There was < 0.03 $cm^3 cm^{-3}$ difference in VWC between the soil moisture determined from these samples and the corresponding daily VWC value derived using the site's initial calibration data. The results from
210 each soil calibration are available in Table 5.

Table 5: COSMOS-UK soil sampling results.

Site name	Date of calibration	Reference soil moisture ($cm^3 cm^{-3}$)	Reference bulk density ($g cm^{-3}$)	Reference lattice water ($g g^{-1}$)	Reference soil organic carbon ($g g^{-1}$)
Alice Holt	04/08/2015	0.266	0.85	0.025	0.042
Balruddery	29/07/2014	0.254	1.34	0.018	0.023
Bickley Hall	24/02/2015	0.412	1.31	0.010	0.020
Bunny Park	25/02/2015	0.283	1.55	0.008	0.016
Cardington	18/08/2015	0.141	1.14	0.016	0.040
Cardington	17/01/2018	0.325	1.30	0.014	0.032
Cwm Garw	28/09/2018	0.417	0.96	0.022	0.048
Chimney Meadows	13/11/2013	0.393	1.36	0.011	0.027
Chimney Meadows	31/08/2018	0.247	1.26	0.011	0.032
Chobham Common	12/03/2015	0.566	0.90	0.003	0.031
Cochno	18/10/2017	0.524	0.83	0.019	0.068
Cockle Park	10/12/2014	0.447	1.21	0.020	0.033
Crichton	08/12/2014	0.428	1.15	0.011	0.045
Easter Bush	16/09/2014	0.303	1.10	0.019	0.033
Elmsett	19/01/2017	0.400	1.26	0.015	0.022
Euston	18/01/2017	0.189	1.27	0.003	0.029
Fincham	28/07/2017	0.279	1.33	0.007	0.02
Fivemiletown	15/11/2018	0.537	0.97	0.014	0.039
Gisburn Forest	17/09/2014	0.542	0.82	0.021	0.061
Glensaugh	28/07/2014	0.608	0.44	0.014	0.203
Glenwherry	20/10/2016	0.631	0.54	0.024	0.153
Hadlow	15/12/2016	0.398	1.22	0.028	0.031

Hartwood Home	30/07/2014	0.356	1.02	0.033	0.043
Harwood Forest	14/06/2017	0.591	0.33	0.009	0.304
Henfaes Farm	06/10/2016	0.507	0.97	0.022	0.077
Hillsborough	19/10/2016	0.450	1.15	0.021	0.042
Holme Lacy	03/05/2018	0.292	1.24	0.017	0.022
Hollin Hill	25/06/2014	0.364	1.06	0.025	0.032
Heytesbury	22/02/2018	0.411	0.88	0.006	0.066
The Lizard	04/11/2014	0.568	0.95	0.014	0.058
Loddington	14/09/2016	0.455	1.16	0.041	0.036
Lullington Heath	14/01/2015	0.452	0.90	0.006	0.043
Moor House	11/12/2014	0.578	0.76	0.014	0.076
Moreton Morrell	13/02/2019	0.433	1.22	0.026	0.035
Morley	19/06/2014	0.161	1.53	0.016	0.017
North Wyke	05/11/2014	0.472	1.12	0.02	0.037
Plynlimon	26/11/2014	0.590	0.62	0.02	0.098
Porton Down	02/02/2015	0.391	0.97	0.004	0.049
Redmere	04/06/2015	0.504	0.60	0.056	0.238
Redhill	08/12/2016	0.252	1.26	0.011	0.024
Riseholme	16/02/2017	0.429	1.27	0.022	0.032
Rothamsted	02/09/2014	0.280	1.33	0.018	0.021
Sheepdrove	20/03/2014	0.327	1.04	0.027	0.059
Sourhope	09/12/2014	0.578	0.65	0.021	0.086
Spen Farm	15/06/2017	0.269	1.41	0.011	0.019
Stoughton	19/11/2015	0.351	1.33	0.018	0.027
Stiperstones	27/11/2014	0.612	0.62	0.016	0.104
Sydling	21/03/2019	0.374	1.17	0.020	0.035
Tadham Moor	06/11/2014	0.615	0.32	0.029	0.314
Waddesdon	13/03/2014	0.460	1.11	0.021	0.034
Wimpole	15/10/2019	0.361	1.22	0.015	0.035
Writtle	27/07/2017	0.350	1.26	0.019	0.035
Wytham Woods	15/04/2014	0.485	1.05	0.017	0.028

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3 COSMOS-UK data

3.1 Deriving soil moisture from the CRNS

Field scale soil moisture (CRNS VWC) is derived from the CRNS fast neutron counts, which inversely correlate with hydrogen present at the land surface (Zreda et al., 2008; Zreda et al., 2012). Fast neutrons collide with hydrogen nuclei at the land surface and are therefore moderated by the hydrogen present in water molecules, thereby enabling an indirect measurement of soil moisture (Rivera Villarreyes et al., 2011). Neutron counts from each site are aggregated to a 60-minute interval and corrected for atmospheric pressure (Desilets, 2017) and humidity (Rosolem et al., 2013) variations using in situ measurements. The atmospheric pressure correction uses instantaneous barometric attenuation lengths (Desilets and Zreda, 2003) calculated for COSMOS-UK sites according to crnslab.org/util/intensity.php. A subsequent correction is applied for background neutron intensity variation (Desilets, 2017; Blake et al., in review), using the publically available data from Physikalisches Institut's Jungfraujoch (JUNG) neutron detector in Switzerland (nmdb.eu/station/jung/). JUNG data are retrieved and used in sub-daily calculations to produce near-real time COSMOS-UK datasets; the period of record is subsequently updated for any changes to JUNG data on an annual basis. Where data are unavailable from the JUNG detector the period is infilled with appropriately scaled values from alternate monitors: another counter at Jungfrau (JUNG1), Newark in the USA (NEWK) or Apatity in Russia (APTY). The resulting corrected counts are then calibrated to the site's specific soil, using the soil calibration values determined by UKCEH laboratory analysis.

COSMOS-UK uses the site-specific N_0 method (Desilets et al., 2010) for deriving water content from a site's corrected neutron count data, where N_0 is the site-specific neutron counting rate over dry soil under reference atmospheric pressure and solar activity conditions. Alternative methods are described in Baatz et al. (2014), Bogena et al. (2015) and Iwema et al. (2015). A site-specific N_0 value is calculated using the average neutron counts on the day of calibration, together with reference soil moisture, reference soil lattice and bound water and reference soil organic carbon as determined for the calibration day by field and laboratory analyses (Franz, 2012; Franz et al., 2013; Zreda et al., 2012; Evans et al., 2016). The calculation also relies on parameters determined by the relationship between corrected neutron counts and soil moisture as defined for a basic silica soil (Desilets et al., 2010). VWC is then derived from the corrected counts using N_0. These data are subsequently constrained to the physical range of 0–100 % soil water content by determining values of N_{max} and N_{min} respectively, the maximum and minimum physically admissible neutron count value for each site. Figure 4 shows an example of the calibration curve for the Redhill site, located in South East England.

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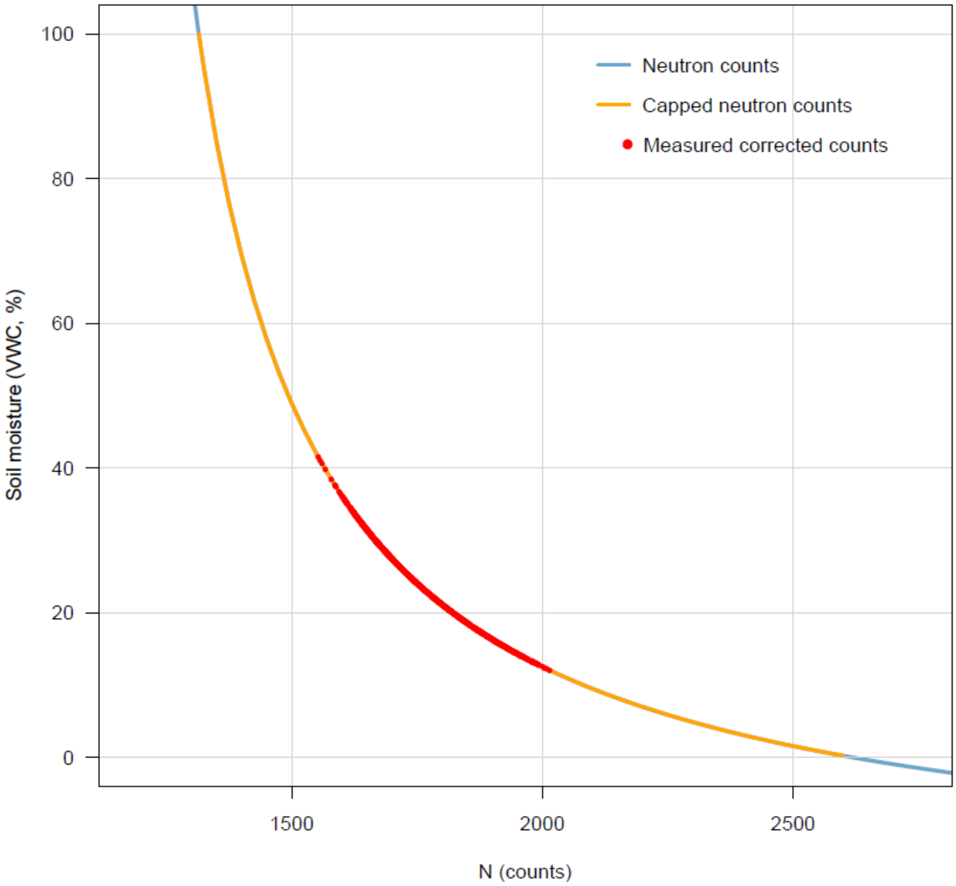

Figure 4: CRNS VWC versus neutron counts for the Redhill site in South East England using the N_0 technique is shown in blue. N_{min} and N_{max} for this site are 1314.75 and 2616.33 respectively as shown by the extent of the orange line. The range of measured corrected neutron counts at this site between 18 February 2016 and 01 September 2020 is shown in red.

Once complete, this process produces the hourly CRNS VWC dataset. In a subsequent process, hourly corrected neutron counts are averaged to a daily mean and undergo the same calculations to produce the daily CRNS VWC soil moisture dataset. A minimum of 20 hourly values in a day is set as the requirement to produce a daily soil moisture value. An additional version of the soil moisture dataset is calculated, in which daily CRNS VWC has been adjusted for snow events using site measurements of albedo.

Point soil moisture and precipitation data at each COSMOS-UK site provide important ancillary information for assessing the potential accuracy of the CRNS VWC data. Figure 5 shows each of the processing stages for deriving soil water content from neutron counts for the Cochno site in Scotland, alongside soil moisture measured by the 10 buried point sensors and precipitation. This figure clearly shows that daily CRNS VWC data closely resemble the soil moisture dynamics measured by the point sensors, and the response of both VWC measurements to precipitation events. Some data uncertainty exists for sites

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with high levels of soil moisture (Blake et al., 2020). These high moisture sites often correspond with extensive soil organic matter accumulation (e.g. carbon-dense peatlands) or mature woodlands where CRNS VWC methods might need to be further refined to account for biomass, plant roots, litter-layer thickness and intercepted water (Andreasen et al., 2017; Baatz et al., 2015; Heidbüchel et al., 2016; Rivera Villarreyes et al., 2011). The contrast of CRNS VWC measurements between sites can be seen in Fig. 6, which displays all data for the period of record as a normalised curve for each site. This figure demonstrates the importance of identifying and understanding localised soil properties, and shows how sites in close proximity and experiencing broadly similar weather patterns can exhibit vastly different ranges and extremes in VWC.

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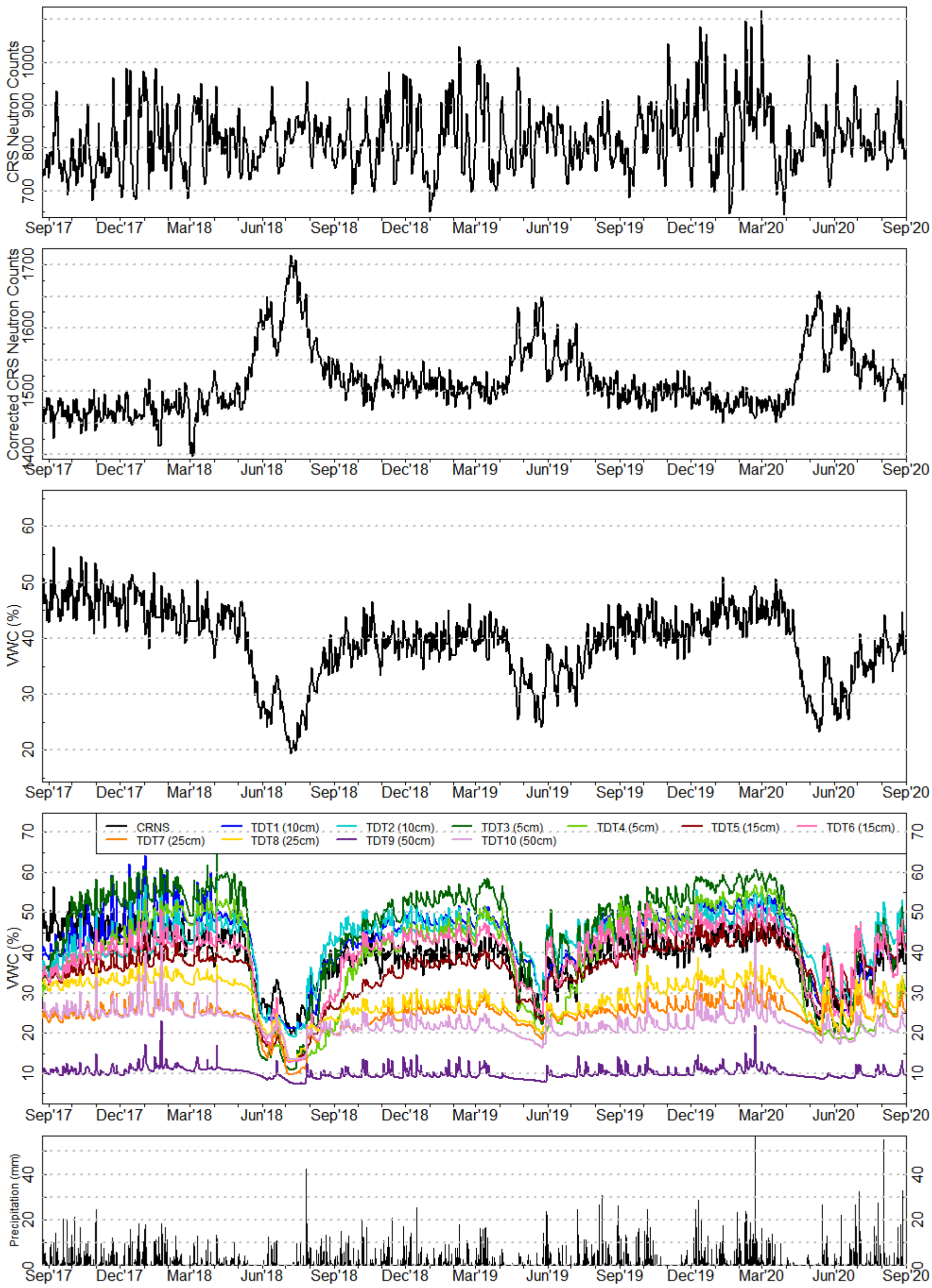

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Figure 5: Daily mean COSMOS-UK data for the Cochno site in Scotland. From top: Raw neutron counts from the CRNS; neutron counts corrected for pressure, humidity and background count intensity; VWC determined from the CRNS corrected counts and corrected for snow; CRNS VWC and point TDT VWC measurements at a series of depths; and precipitation. Note the 2018 cold wave and summer heatwave impact on soil moisture.

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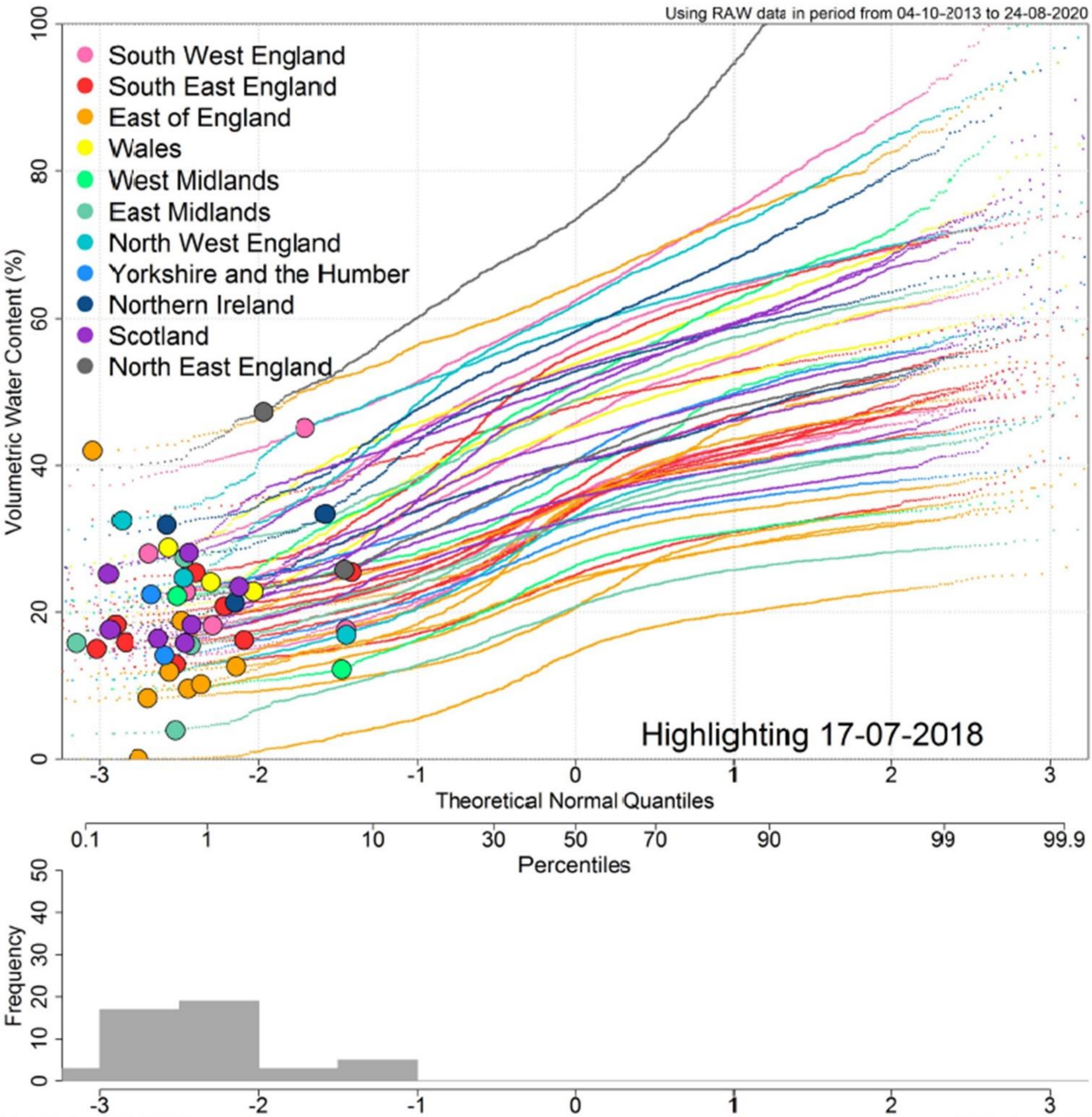

Figure 6: Soil moisture regime plot for all COSMOS-UK sites grouped by region (dot colour) according to the Nomenclature of Territorial Units for Statistics (NUTS) codes of the United Kingdom. Each line represents the distribution of CRNS VWC at a COSMOS-UK site; sites with wetter regimes plot higher up in the figure. The dots and histogram represent the soil moisture and corresponding frequency, respectively, on 17 July 2018 when there was a widespread drought across the UK.

3.2 Soil moisture measurement area and depth

The CRNS VWC value is an average soil moisture measurement (%) across an estimated, variable footprint of radius up to 200 m, and estimated, variable measurement depth of between approximately 0.1 and 0.8 m (following Köhli et al., 2015). Measurement area depends on local soil moisture, humidity and land cover (Köhli et al., 2015), whilst penetration depth depends on soil moisture as well as lattice water and soil organic matter water equivalent (Zreda et al., 2008; Franz et al., 2012; Zreda et al., 2012). The greater the actual soil water content, the smaller the CRNS measurement area and shallower the penetrative depth. The measurement area of the CRNS was initially believed to have a radius of approximately 300 m (Zreda et al., 2008); however Köhli et al., (2015) report that 50 % of measured neutrons originated within 50 m of the CRNS, and the footprint radius extended to only 240 m in arid climates. The penetration depth of the measurement is greatest near the CRNS and decreases with distance from the sensor; this varying depth across the footprint is provided as 'D86', the depth at which 86 % of the measured neutron counts are estimated to have originated at a given distance (Zreda et al., 2008; Franz et al., 2013). In the COSMOS-UK dataset, D86 is provided at distances of 1, 5, 25, 75, 150 and 200 m from the CRNS. Figure 7 shows the D86 measurements for a typically drier site, Euston (average soil moisture approximately 15 %) and a typically wetter site, Riseholme (average soil moisture approximately 33 %) for 2018. During this year the UK experienced a cold wave with significant snow in February to March and a heatwave in June to August. This figure presents how measurement depth increases in drier conditions, decreases with distance from the CRNS, and differs between sites.

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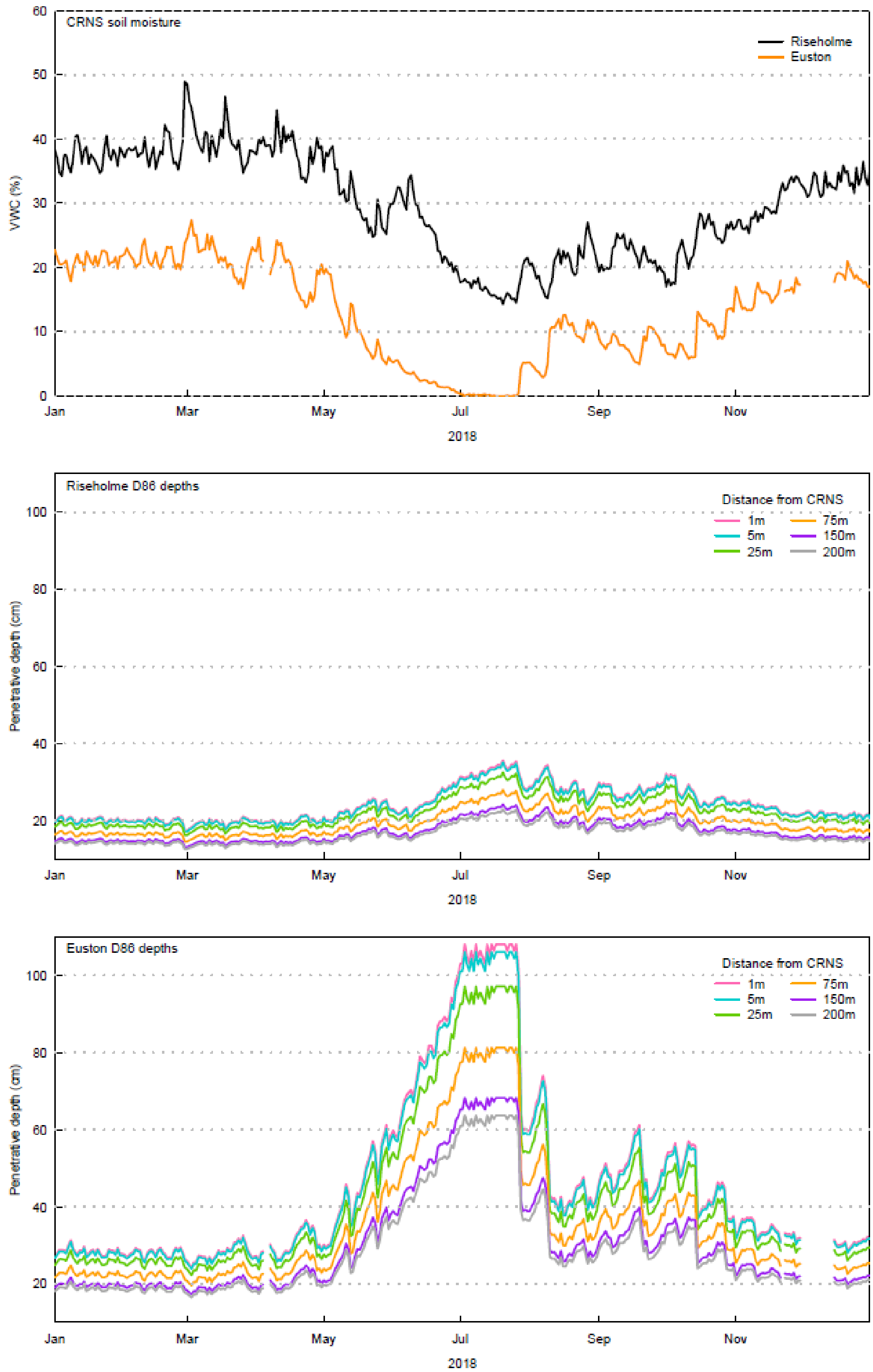

295 **Figure 7: CRNS VWC and corresponding D86 penetrative depth measurements (cm) for two sites, Riseholme in the East Midlands and Euston in East Anglia, throughout 2018.**

3.3 Data processing and quality procedures

Raw data collected at each COSMOS-UK site, comprising the measured variables described above as well as additional diagnostic data from sensors (e.g. internal humidity of the CRNS), are telemetered to UKCEH and stored in an Oracle relational database (Oracle, 2013). When new values are derived following the application of corrections, calibrations and quality tests, these derived data are stored in separate, secondary, tables. These secondary datasets are those that are published.

Data quality assurance (QA) and quality control (QC) are applied to specific variables in the raw data. QC is conducted in two stages:

1. Automated processing is applied to raw data to provide a quality assured dataset. Data which fail the tests are flagged and are not written to secondary datasets. These automated tests include pre-processing for known errors and subsequent QC processes for detecting additional erroneous data. These processes are explained below.
2. Regular manual inspection of raw, diagnostic and processed data is performed using a variety of automated summary plots and reports. Clearly erroneous data that have passed the automated QC tests are flagged and omitted from the secondary dataset.

Automated processing tasks assess the raw data and create a flagged dataset based on the test results. This enables tracking of data removal and ensures raw data are not lost or overwritten. Unique flag values are assigned to raw data values where the data fails a specific QC test (Table 6). Where data pass all QC tests, the flag values are assigned '0'. The tests flag issues including: data exceeding known thresholds; implausible values; and data where other variables indicate an issue. The secondary dataset comprises all data not flagged by the QC processes.

All derived datasets are obtained using the quality checked 30 minute data. Planned future work includes the development of a tertiary dataset comprising quality processed and gap-filled data.

Table 6: Unique flag values assigned to data based on QC test results.

Test	Flag description	Flag value
	Passes all tests	0
Missing	Fails the test for missing values	1
Zero data	Fails the test for zero values where impossible	2
Too few samples	Fails if not enough samples taken by the data logger over the data interval	4
Low power	Fails if the site battery level is too low	8
Sensor faults	Fails where sensor has been manually recorded as faulty for a period of the record	16
Diagnostic	Fails based on diagnostic data for particular sensors	32
Range	Fails if values are outside a predefined range for the variable	64

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Secondary variables	Fails if a value of one variable implies a fault with another	128
Spike	Fails where a spike in the data exceeds a given threshold	512
Error codes	Fails where data contains any known error code	1024

3.4 Derived data

In addition to the COSMOS-UK observed soil and hydrometeorological data, the network provides derived datasets including potential evaporation (PE), albedo, snow days and snow water equivalent (SWE).

PE has been derived from each site's solar radiation, soil heat flux, air temperature, humidity, and wind speed data using the Penman-Monteith method as described by the Food and Agriculture Organization of the United Nations (FAO) (Allen et al., 1998) (Fig. 8). 30 minute and daily PE for all COSMOS-UK sites are provided in this dataset.

Snow days have been identified using albedo measurements and SWE has been determined using the albedo and neutron count data available at each COSMOS-UK site. Neutron counts from both the CRNS and SnowFox sensor are sensitive to all sources of water in the environment, allowing them to be used to estimate the SWE held in a snow pack. First the albedo is used to determine the presence or absence of snow cover and then, if present, the reduction in neutron count rate from an estimated snow free value is used to approximate the SWE, following the method of Desilets (2017). Alternative methods for estimating SWE are available from Wallbank et al. (2020b) and discussed in more detail in Wallbank et al. (2020a).

Available derived data are listed in Sect. 4.

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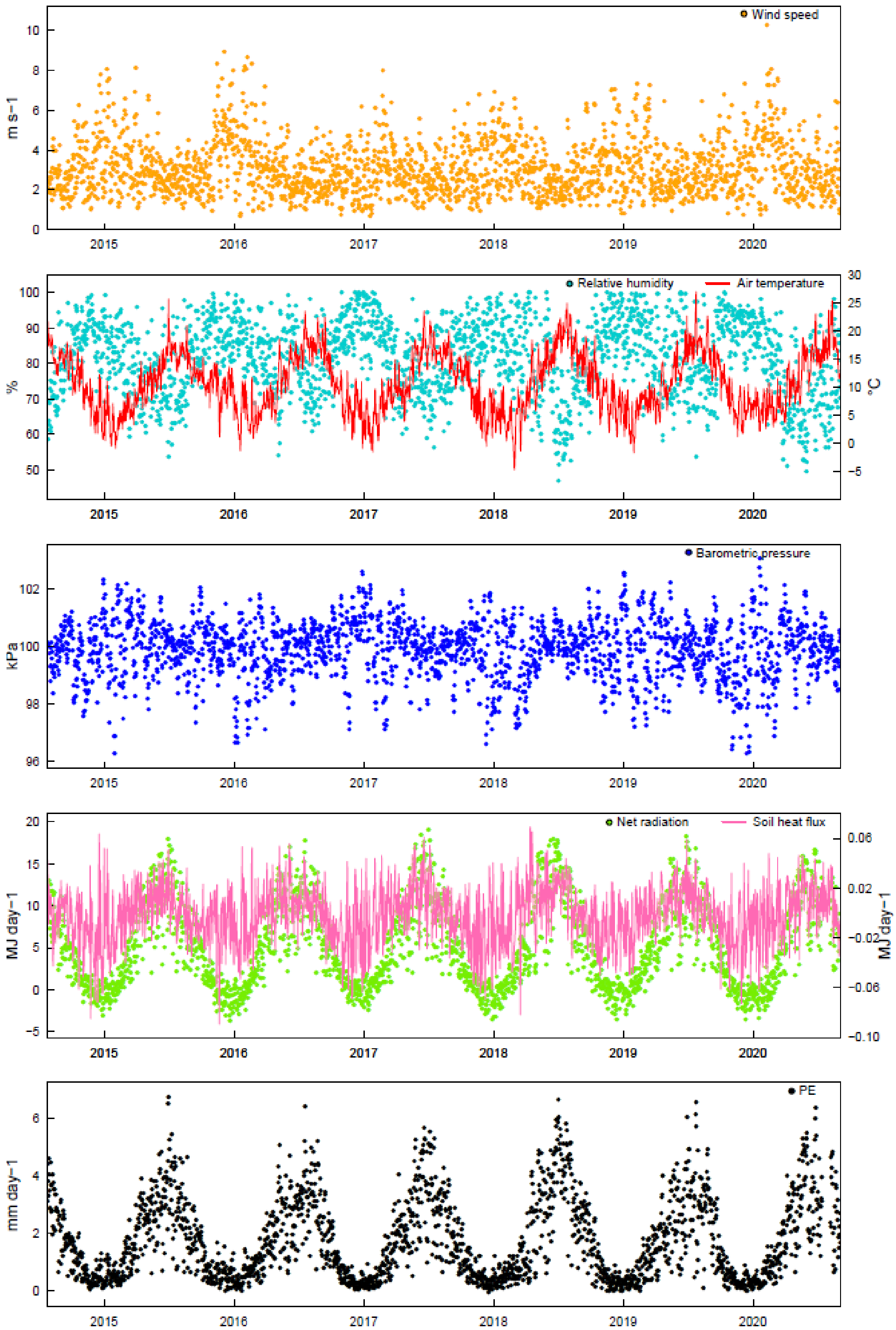

335 **Figure 8: COSMOS-UK observations required for the calculation of Potential Evaporation (PE) at the Rothamsted site in East Anglia.**

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3.5 Additional available data

Additional information can be derived from the data provided by COSMOS-UK sites. As part of ongoing and planned evolution of the network, the additional data described in this section are not yet included in the published data.

Existing PE data will be complemented by a new derived dataset, which estimates actual evapotranspiration (ET) as the residual term from measurements of net radiation, soil heat flux and the sensible heat flux derived from sonic anemometer measurements. Modelled energy fluxes, such as latent and sensible heat, have been calculated by utilising the 20 Hz wind measurements recorded at the majority of COSMOS-UK sites (Crowhurst et al., 2019). This provides a network-wide modelled actual ET dataset for the UK.

In addition to the measurements mentioned previously, COSMOS-UK sites also capture photographs. Sites include a camera for monitoring phenology, a 'PhenoCam', with two hemispheric lenses facing north and south (Fig. 9). Each COSMOS-UK site sends five photographs per day, which capture the full extent of the COSMOS-UK site and surrounding area, thereby providing additional information on local phenology and cloud cover. These PhenoCam images can be used to confirm when site conditions have changed, for example when the land cover has been modified (e.g. ploughing, mowing, grazing, harvesting) or there has been heavy snowfall. PhenoCam photos from COSMOS-UK sites are also currently being analysed to produce a greenness dataset. Using site-specific image masks, RGB (red, green, blue) data can be extracted from each image to determine the greenness of the land cover at each site (Wingate et al., 2015). In 2020 the network's first gauge board was installed at the Cwm Garw site in Wales; as gauge boards are installed across the network, new vegetation height and snow depth data will become available via the PhenoCam images.

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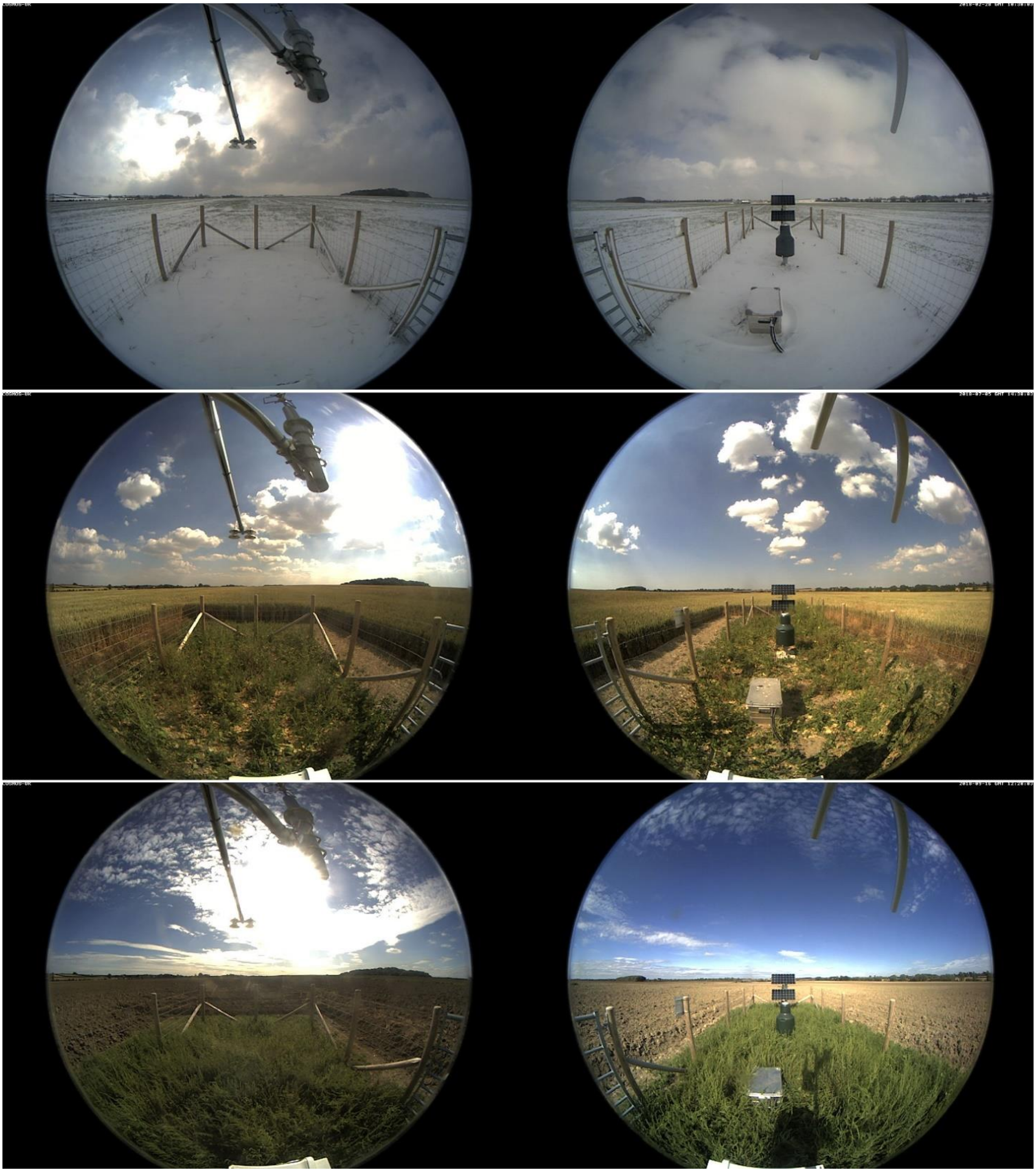

Figure 9: PhenoCam photographs from the Fincham COSMOS-UK site in East Anglia. From top: a snow event at the end of February 2018; oil seed rape crop growing in surrounding field in July 2018; and the bare field in September 2018.

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4 Data availability

The "Daily and sub-daily hydrometeorological and soil data (2013-2018) [COSMOS-UK]" time series dataset is the most recent COSMOS-UK dataset at the date of publication. The dataset is published by, and available for download from the EIDC at https://doi.org/10.5285/37702a54-b7a4-40ff-b62e-d14b161b69ca (Stanley et al., 2020).

This dataset comprises daily and sub-daily observations and derived data between 02 October 2013 and 31 December 2018 inclusively for 50 sites across the UK. The files included for each site are:

1. COSMOS-UK_[SITE_ID]_HydroSoil_SH_2013-2018.csv
2. COSMOS-UK_[SITE_ID]_HydroSoil_SH _2013-2018_QC_Flags.csv
3. COSMOS-UK_[SITE_ID]_HydroSoil_Hourly_2013-2018.csv
4. COSMOS-UK_[SITE_ID]_HydroSoil_Daily_2013-2018.csv

Table 7 comprises the measured and derived variables, units and recording interval of data available in these files. File 1 contains measured and derived variables at 30 minute resolution and file 2 comprises the QC flags for the data in file 1. File 3 comprises the derived variables available at hourly resolution and file 4 contains derived data at daily resolution.

Table 7: Measured and derived variables available in the 4 data files provided in the COSMOS-UK dataset (Stanley et al., 2020).

Variable	Unit	Recording interval	Data type	Data resolution	File
Precipitation	mm	1 min	Measured	30 min	1
Relative humidity	%	30 min	Measured	30 min	1
Absolute humidity	gm^{-3}	30 min	Derived	30 min	1
Air temperature	°C	30 min	Measured	30 min	1
Atmospheric pressure	hPa	30 min	Measured	30 min	1
Incoming longwave radiation	Wm^{-2}	30 min	Measured	30 min	1
Incoming shortwave radiation	Wm^{-2}	30 min	Measured	30 min	1
Outgoing longwave radiation	Wm^{-2}	30 min	Measured	30 min	1
Outgoing shortwave radiation	Wm^{-2}	30 min	Measured	30 min	1
Net radiation	Wm^{-2}	30 min	Derived	30 min	1
Wind direction	degrees	30 min	Measured	30 min	1
Wind speed	ms^{-1}	30 min	Measured	30 min	1
3D wind speed data (x3)	ms^{-1}	20 Hz	Measured	30 min	1
Snow depth	mm	30 min	Measured	30 min	1
Soil heat flux (x2)	Wm^{-2}	30 min	Measured	30 min	1
Soil temperature (x5)	°C	30 min	Measured	30 min	1
Soil temperature (TDT) (x2 or x10)	°C	30 min	Measured	30 min	1

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Soil moisture (TDT VWC) (x2 or x10)	%	30 min	Measured	30 min	1
Soil moisture (CRNS VWC)	%	Hourly	Derived	Hourly & Daily	3 & 4
Effective depth of CRNS (D86 at 75 m)	cm	Hourly	Derived	Hourly & Daily	3 & 4
Neutron counts from CRNS (corrected)	counts	Hourly	Derived	Hourly	3
Potential evaporation	mm	Daily	Derived	Daily	4
Albedo	Dimensionless	Daily	Derived	Daily	4
Snow days	Yes/No	Daily	Derived	Daily	4
Snow Water Equivalent (from CRNS)	mm	-	Derived	Daily	4

Site metadata are available in an additional file:

5. COSMOS-UK_SiteMetadata_2013-2018.csv

Data availability for individual variables and sites varies throughout the dataset due to sensor faults, planned preventative maintenance, and disruptions to data collection. Overall data completeness for this period for available variables is 95.6% (see a summary in Fig. 10) (Stanley et al., 2020). Missing values due to technical faults and failed QC calculations are recorded -9999.

Further data will also be made available via the EIDC. The dataset is superseded annually, with the inclusion of one additional year of COSMOS-UK data for all available sites. Data are provisional and subject to change with the release of each new version in line with developments to the science, data processing, quality control and data gap-filling protocols. Data are supplied with supporting information and a data licence that outlines the terms of use to data users.

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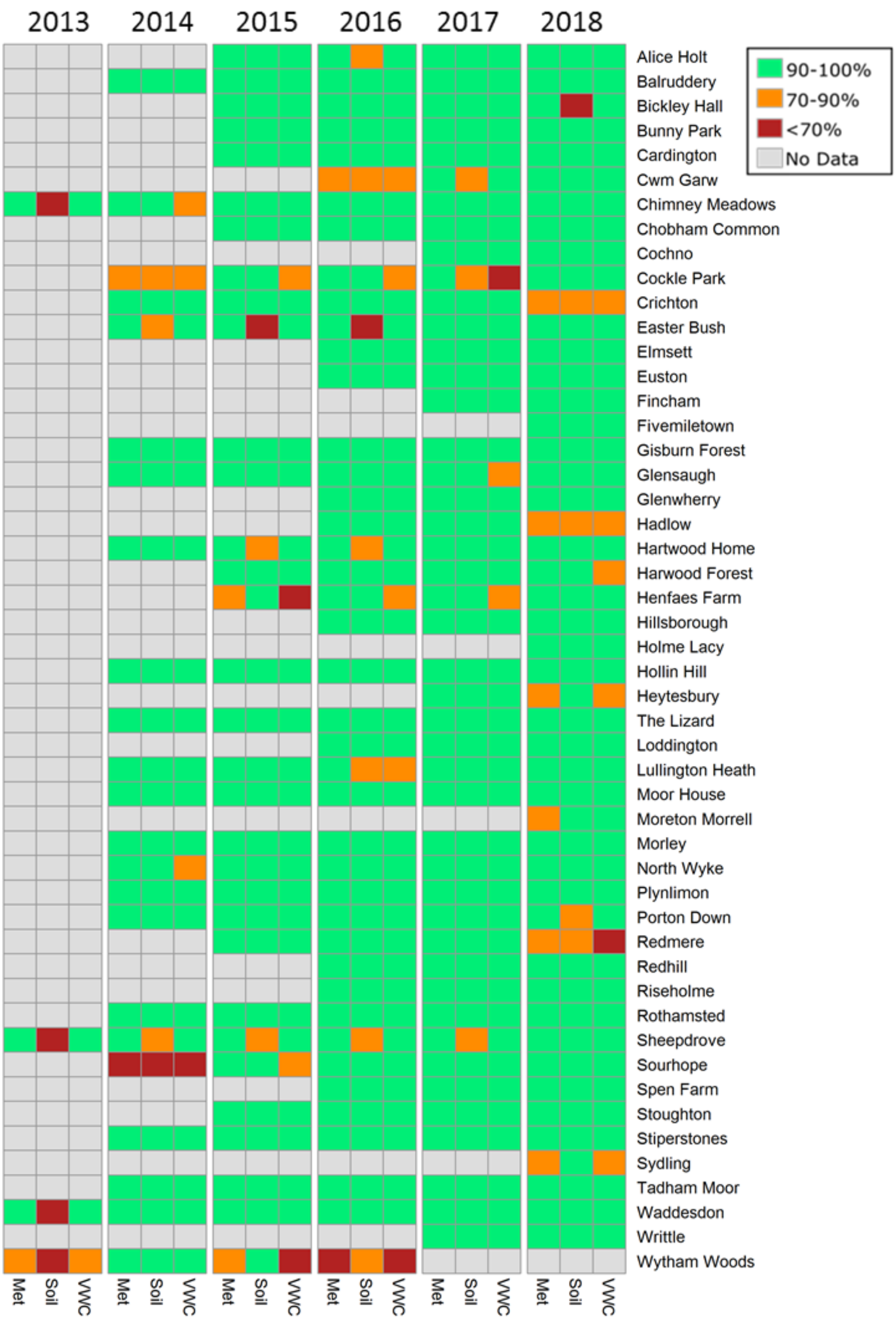

Figure 10: Data completeness for the Stanley et al. (2020) COSMOS-UK dataset. 'VWC' is the CRNS VWC data; 'Soil' consists of data from buried point and profile soil moisture sensors; and 'Met' comprises meteorological variables.

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5 Data applications

Observational data from the COSMOS-UK network have been used for a variety of purposes. They have significant potential to empower a range of existing and novel scientific applications. Descriptions of some uses are included in this section. The main and immediate applications for COSMOS-UK observational data are for use in hydrological and land-surface models and for validating remote sensing data.

COSMOS-UK measurements cover a range of environmental characteristics and this can be exploited for model driving data and further development of models, which are used for scaling up and forecasting soil moisture at the national scale. Field scale soil moisture measurements from a variety of land covers have been used to investigate the accuracy and reliability of LSMs. Comparison of COSMOS-UK soil moisture measurements with outputs from LSMs allows for investigation into those models' ability to represent soil moisture dynamics and underlying physical processes (Cooper et al., 2020a). For example, data assimilation techniques have been used to adjust soil physics parameters (via pedo-transfer functions), thereby allowing the JULES model to more closely produce the observed range of soil moisture values (Cooper et al., 2020b). This demonstrates the value in using in situ COSMOS-UK data to drive models for increased performance. Additional potential exists in using these larger area data across a variety of land covers to explore interactions and dynamics in infiltration, run-off (Dimitrova-Petrova et al., 2020) and interception (Zreda et al., 2012). Improved understanding of these processes could lead to more accurate and reliable modelling of, and thus improved forecasting for, a range of hydrological phenomena.

Using land-atmosphere modelling together with COSMOS-UK soil moisture and modelled ET data, along with measured ET where available, can empower further investigation into soil moisture dynamics and biosphere-atmosphere fluxes. These combined data can provide greater understanding of land-atmosphere processes, for example of feedback events during periods of drying soils and extreme air temperatures (Dirmeyer et al., 2020) and storm initiation (Taylor et al., 2012). Use of these data can also help estimate landscape average precipitation, as described in Franz et al. (2020).

COSMOS-UK field scale soil moisture is also proving particularly useful for ground-truthing remote sensing soil moisture data. For this application, the value of COSMOS-UK data largely resides in the footprint of the CRNS. The field scale soil moisture data prove to be a radical improvement on point soil measurements alone, as the larger footprint more closely represents the resolution of satellite products, whilst averaging across smaller-scale soil heterogeneity. COSMOS-UK data can therefore help validate and improve existing products (Beale et al., 2020; Pinnington et al., 2020; Quinn et al., 2020) for obtaining better estimates of UK soil moisture data at higher spatial resolution (Peng et al., 2020). Similar networks across the globe, for example in the US, India and China, have also been exploited for such research (Montzka et al., 2017; Zhu et al., 2019). COSMOS-UK soil moisture can be used together with PhenoCam data to further investigate remote sensing analysis in vegetation growth, crop senescence, snow events, surface ponding, and land cover change.

With a vision to develop a dynamic near-real time UK soil moisture map, there is potential for COSMOS-UK data to influence wider fields. Scaled up near-real time COSMOS-UK data either through using models, remote sensing, or both could inform water-regulators such as the Environment Agency on the state of UK soil moisture. Direct evidence of drought and flooding events induced, or impacted, by soil moisture is increasingly needed to inform decisions at national scale. Similarly, these data could help inform UK wildfire prediction and ecological applications via simulations of soil moisture, air temperature, precipitation, and vegetation information (Albertson et al., 2009). Additionally, with an understanding of the links between soil moisture and plant productivity, COSMOS-UK data can be used to monitor the need for irrigation (Ragab et al., 2017), thereby improving our predictions of crop yield for the UK. Furthermore, understanding soil moisture at identified landslip sites could help in the development of Landslide Early Warning systems, for example using the Hollin Hill COSMOS-UK site in North Yorkshire (Bliss et al., 2020).

COSMOS-UK data could also provide insight into alternative scientific research, such as the relationship between soil moisture and pest behaviour (Hertl et al., 2001); the impact of soil moisture on local infrastructure (Pritchard et al., 2013); investigation of ground level cosmic ray events (Flückiger et al., 2005); and meteorological data with respect to bacterial infection seasonality (Djennad et al., 2019).

6 Conclusions

The COSMOS-UK network is the world's most spatially dense national network of cosmic-ray neutron sensors for observing near-surface field scale soil water dynamics. Field scale soil moisture and hydrometeorological data are available from a diverse range of sites located across the UK, with the earliest sites providing data since 2013. The COSMOS-UK dataset is a unique and growing resource that has already captured soil water dynamics across a wide range of climatic conditions, including extreme events such as the extended cold wave, heatwave and agricultural drought the UK experienced during 2018.

As the length of the data record continues to grow, COSMOS-UK will provide an unprecedented resource for national scale environmental monitoring. Data from the COSMOS-UK network are of significant national and international relevance empowering applications including the validation of remotely sensed data products, the interpretation of biogeochemical flux observations, and the calibration and testing of LSMs. Significant opportunity exists for new applications in support of water resources, weather prediction and space sciences, and biodiversity and environmental change.

At the time of publication, the most recent COSMOS-UK dataset available comprises daily and sub-daily hydrometeorological and soil physics data between 02 October 2013 and 31 December 2018 for 50 sites. The COSMOS-UK dataset will be updated on an annual basis.

Team list

The following UKCEH team members currently contribute to the success of the COSMOS-UK network: Joshua Alton, Vasilieous Antoniou, Anne Askquith-Ellis, Lucy Ball, Milo Brooks, Michael Clarke, Sandie Clemas, Nicholas Cowan, Richard Ellis, Jonathan Evans, Phil Farrand, Charles George, Duncan Harvey, Sarah Leeson, William Lord, Gemma Nash, Peter Scarlett, Andrew Singer, Charlie Stratford, Oliver Swain, John Wallbank and Alan Warwick. The following team members

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Author contributions

The initial draft manuscript was prepared and written by HC with significant contributions from JB, DB and SS. Additional contributions were made by E Bennett, E Blyth, EC, MF, AJ, RM, DR, MS and ET.

Competing interests

The authors declare that they have no conflict of interest.

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