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Soil water content in southern England derived from a cosmic-ray soil moisture observing system – COSMOS-UK

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Abstract

Cosmic-ray soil moisture sensors have the advantage of a large measurement footprint (approximately 700 m in diameter) and are able to operate continuously to provide area-averaged near-surface (top 10-20 cm) volumetric soil moisture content at the field scale. This paper presents the application of this technique at four sites in southern England over almost 3 years. Results show the soil moisture response to contrasting climatic conditions during 2011-2014, and are the first such field-scale measurements made in the UK. These four sites are prototype stations for a UK COsmic-ray Soil Moisture Observing System (COSMOS-UK), and particular consideration is given to sensor operating conditions in the UK. Comparison of these soil water content observations with the Joint UK Land Environment Simulator (JULES) 10 cm soil moisture layer shows that these data can be used to test and diagnose model performance, and indicates the potential for assimilation of these data into hydro-meteorological models. The application of these large-area soil water content measurements to evaluate remotely-sensed soil moisture products is also demonstrated. Numerous applications and the future development of a national COSMOS-UK network are discussed.

Keywords

Soil water content; soil moisture; COSMOS; COSMOS-UK; JULES; soil moisture deficit; cosmic-ray soil moisture sensor; ASCAT

1 Introduction

Soil moisture plays a central role in the hydrological cycle and surface energy balance. As a state variable, knowledge of soil moisture (SM) is required for modelling of water resources, floods and droughts, eco-hydrology, agronomy, weather prediction, climate forecasts and modelling of greenhouse gas exchanges. In meteorological models the soil moisture content is estimated at many depths as part of the land-surface scheme (e.g. Best *et al.*, 2011). The performance of this soil moisture component requires evaluation, and has sometimes been shown to have large bias errors when compared to *in situ* observations. For example, the soil moisture product from the European Centre for Medium Range Weather Forecasting (ECMWF) has been shown to have constant bias errors of 0.1-0.2 $m^3 m^{-3}$ for four test sites in the US (Leroux *et al.*, 2014). However, there is generally very little *in situ* data with which to compare model results. Recently, progress has been made in assimilation of satellite soil moisture products, such as those from the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) mission and the Advanced Scatterometer (ASCAT) on the Metop satellite (Dharssi *et al.*, 2011). Satellite SM products have the key advantage of global or quasi-global coverage, but with disadvantages of relatively poor spatial resolution (≈50 km), shallow measurement depth (circa 5 cm) and technical interference caused by vegetation and radio communications (Al-Yaari *et al.*, 2014). Notwithstanding this, these data can be used to improve forecast models (Dharssi *et al.*, 2011). There is an urgent need to provide ground truth observations for satellite SM products, especially as higher spatial resolution products become available, such as NASA's Soil Moisture Active Passive (SMAP) mission (10 km resolution) (Entekhabi *et al.*, 2010), or Sentinel-1 (resolution below 100 m) (Paloscia *et al.*, 2013).

There are very few *in situ* field data representative of a scale that is comparable with model or satellite data (i.e. measurements at the field-scale or greater) which average across spatial heterogeneity and could provide systematic replication across the UK. The advent of a new technique, the cosmic-ray soil moisture sensor (CRS), to measure soil moisture area-averaged over a footprint of about 700 m in diameter (Zreda *et al.*, 2008), enables a step-change in our monitoring capability. In this paper we describe preliminary studies undertaken as part of a new initiative to establish a COsmic-ray Soil Moisture Observing System in the United Kingdom (COSMOS-UK) to systematically measure volumetric soil moisture content across the UK.

Until a few years ago, most ground-based soil moisture measurements (with the notable exceptions of lysimeters and passive microwave techniques), have only been able to sample very small volumes of soil (cubic decimetres) (Robinson *et al.*, 2008). Although there is a large variety of ‘point’ sensors commercially available, they are limited to representing the small-scale heterogeneity of soils unless numerous point sensors are deployed at a particular site, which is both costly and inconvenient. Whilst point sensors may remain useful for many applications such as irrigation control and process studies (and they are also very low cost), they are in general unlikely to be representative of the average soil moisture content across hundreds of meters, unless soil properties happen to be highly uniform at that scale.

The CRS measurement principle is similar to the neutron probe developed at Wallingford, UK (Institute of Hydrology, 1981), however it does not require an artificial radioactive neutron source but instead utilises naturally occurring neutrons generated by cosmic rays. This brings both practical and logistical advantages and dramatically increases the potential of SM monitoring by neutron detection, since the CRS can be deployed in the field unattended, for long-term or semi-permanent installations, and may provide continuous records of soil moisture over several years or decades. The technique is non-invasive: the neutron detectors are installed just above the ground so access tubes are not required, and a single CRS passively measures the whole footprint from a position at the centre. The biggest advantage offered by the CRS is the scale of the measurement: a circular footprint with a radius of approximately 350 m. Observations of soil moisture at this scale are hugely valuable, yet impractical to obtain routinely with point measurements simply because of the vast number that would be required. The volumetric soil moisture content obtained from the CRS is spatially-integrated and representative of near-surface conditions. Each probe detects fast neutrons which have been generated from cosmic rays. At the Earth's surface, fast neutrons are absorbed by hydrogen atoms (predominantly in water molecules), so fewer neutrons detected implies a higher water content (Desilets *et al.*, 2010). The neutron count is thus related to SM and other stores of hydrogen, such as that contained within biomass (Franz *et al.*, 2012).

Desilets *et al.* (2010) suggested that the CRS could be used at a fixed site for *in situ* SM monitoring, or in a moving vehicle for mapping soil moisture over large areas. The practical application and challenges of mapping soil moisture over large areas using the cosmic-ray rover were first described by Chrisman and Zreda (2013). Suitable near-surface (0 – 5 cm) accuracy of the rover for comparison with satellite SM products was reported by Dong *et al.* (2014), who found the rover to provide a valuable technique for the calibration and validation of microwave remote sensing missions.

The next section details the site characteristics of four prototype stations. The standardised COSMOS-UK prototype monitoring station is described in Section 2.2, and data processing in Section 2.3. The field calibration methodology is set out in Section 2.4. Soil moisture data from the four sites during an exceptionally wet winter 2013/14 are presented. A longer time series (almost 3 years) for two sites are analysed and compared with satellite SM data

(ASCAT) and land-surface model output (Section 4). Finally, a summary and outlook for the development of a national COSMOS-UK network is given in Section 5.

2 Methodology

2.1 Description of sites

Figure 1 shows the location of the four prototype COSMOS-UK stations in southern England. These have been operational as standardised prototype stations since late 2013; however Chimney Meadows (CHIMN) and Sheepdrove Organic Farm (SHEEP), have CRS datasets extending back to 2011 (Table 1).

The CHIMN site is low-lying (66 m Above Ordnance Datum, AOD) within 500 m of the upper River Thames, with a shallow water table, and is on fairly natural (restored) meadow grassland (http://www.bbowt.org.uk/reserves/chimney-meadows). Further site information is given in Table 1. In contrast, SHEEP is high on the West Berkshire Downs (183 m AOD), and the underlying geology is highly permeable white chalk, with the water table typically many tens of meters below the surface. The Waddesdon Manor (WADDN) site is on a gentle slope but poorly drained due to the clay to loam soil type overlaying clay formations. At Wytham Woods (WYTH1), the soils and underlying geology are clays over mudstone downslope of the location and loams over sandstone and limestone upslope. The hydrological response is therefore complex, with the potential for spring line seepage development. Both SHEEP and WADDN are on grazed grassland with predominantly beef cattle at SHEEP and sheep at WADDN. SHEEP is under organic management, and this is reflected in the relatively high soil organic matter content (Table 1). WYTH1 is an area of protected ancient deciduous woodland which is under natural management, with little or no human intervention.

2.2 Instrumentation

Each prototype COSMOS-UK station (Figure 2) is equipped with research-quality meteorological and soil monitoring sensors. Large-area soil moisture is provided by the CRS probes (CRS-1000/B, Hydroinnova, New Mexico). Point measurements of soil moisture are also available from two near-surface TDT (time domain transmissometry) probes (SDI-12 Digital Soil Moisture Transducer, Acclima, Idaho) installed at a depth of 0.10 m and from a profile probe (Trime PICO-Profile, IMKO, Germany) measuring at three depths (0.15, 0.40 and 0.65 m). Soil temperature is measured by the near-surface TDT probes and also at five depths (0.02, 0.05, 0.10, 0.20 and 0.50 m) by a thermocouple profile (STP01, Hukseflux, The Netherlands). Two soil heat flux plates (HFP01SC, Hukseflux, The Netherlands) are installed at a depth of 0.03 m; these plates have a self-calibrating feature to maximise measurement accuracy; the *in situ* calibration is performed once a day. The net radiation is calculated from the four components recorded individually, i.e. incoming and outgoing shortwave and longwave radiation (NR01, Hukseflux, The Netherlands). An automatic weather station (MetPak, Gill Instruments, UK) provides key meteorological variables (screen air temperature, relative humidity and barometric pressure) at a height of 2.0 m. Wind speed and direction are measured using a 2-D sonic anemometer (Windsonic, Gill Instruments) mounted directly above the Metpak temperature screen. Precipitation is measured using a weighing precipitation gauge (Pluvio^2, Ott, Germany) capable of giving precipitation amount and intensity. At WYTH1, where the tree canopy is many metres above the surface, the automatic weather station and four-component radiometer are installed above the canopy, along with a funnel which feeds the weighing rain gauge installed at ground level. A camera (S14, Mobotix, Germany) with almost 360° field of view gives a visual record of the land surface (e.g. state of vegetation, snow cover, ponding water) as well as atmospheric visibility and cloud cover. Data are logged (CR3000, Campbell Scientific Ltd., UK) at 30-min intervals.

Rainfall amount and intensity are also available at 1-min intervals. Each station is powered from a battery and solar panels.

At CHIMN, SHEEP and WYTH1 (where there is a large biomass), bare CRS tubes are installed to measure thermal neutrons, as well as the basic setup using moderated tubes measuring fast neutrons (from which SM is ordinarily derived, Section 1). The interpretation of count rates of neutrons of different energies is a topic of ongoing research but it is thought that additional information about the hydrogen stores can be inferred, such as melting and accumulation of snow (e.g. Desilets *et al.*, 2010; Rivera Villarreyes *et al.*, 2011; Zreda *et al.*, 2012).

In the UK, fast neutron count rates are relatively low so counts must be averaged over long time periods to sufficiently reduce counting noise, imposing a limit on the temporal resolution. Similar results have been found for other cool and wet northern latitude lowlands, such as for some sites in Germany (Bogena *et al.*, 2013). Firstly, for low altitude sites (which have relatively high air pressure, i.e. relatively high air density), fewer high energy neutrons reach the ground as they get moderated to lower energies as they travel through the atmosphere. Secondly, high soil moisture content means that fewer fast neutrons escape from the soil – the measurement principle itself. Thirdly, due to the non-linear calibration curve, under wet conditions a given noise level in the count rate is interpreted as larger change in SM than would be the case under drier conditions.

2.3 Data collection and derivation of soil water content

A main objective of the prototype COSMOS-UK stations is to supply research-quality meteorological and soil data in near-real time, which can be assimilated into hydro-meteorological models and flood forecasts or to inform about surface conditions on-site. To accomplish this, each station is fitted with a modem which transmits data back to a central server every hour. Automated scripts check the most recently collected data and write to a database linked to the COSMOS-UK website (ceh.ac.uk/cosmos), allowing remote viewing of data.

Basic quality control procedures are applied to the automated data stream. These reject data under the following circumstances: when there is a known sensor fault; if an instrument diagnostic flag has been set; if data exceed physically reasonable thresholds; and if the sample period is too short. Neutron counts are also subjected to a simple despiking algorithm based on the change in counts between adjacent data points. However, there may be some issues which require more sophisticated quality control and diagnosis and are not flagged up in near-real time. For this reason, real-time data are provisional and subject to change following manual verification offline.

Estimating soil moisture from measured neutron counts requires the application of several corrections followed by calibration based on field samples. For the COSMOS-UK data, the following procedure is applied:

1. Neutron counts and meteorological data are averaged to 60 min.
2. Several correction factors are applied to the neutron counts.
    a. Neutron counts are corrected for the influence of atmospheric pressure (Hydroinnova, 2013),

$$F_p = \exp[\beta(p - p_0)], \tag{1}$$

where F_p is the pressure correction factor and β is the barometric pressure coefficient. Barometric pressure, p, is measured on site (Section 2.2) and an arbitrary value of 1000 hPa is used for p_0 (note that the corrected counts are not directly comparable across the network without additional consideration of the site altitude – for COSMOS-UK this is inherently integrated into the SM calibration). A value of β = 1/130 hPa^{-1} was used across all sites, although there is a small dependence on latitude (Zreda *et al.*, 2012).

b. Neutron counts are corrected for the influence of atmospheric water vapour (Rosolem *et al.*, 2013),

$$F_Q = 1 + 0.0054(Q - Q_0), \tag{2}$$

where F_Q is the humidity correction factor, Q is absolute humidity (in g m^{-3}) and Q_0 is the average absolute humidity (in g m^{-3}) during calibration. Absolute humidity is calculated from temperature and relative humidity measured on site (Section 2.2).

c. Neutron counts are corrected for variations in background intensity based on data collected at Jungfraujoch International Geophysical Year (IGY) neutron monitoring station (JUNG) and available from the neutron monitoring database (nmdb.eu), using the equation

$$F_C = \frac{C_0}{C}, \tag{3}$$

where F_C is the intensity correction factor, C is the count rate at Jungfraujoch monitoring station and C_0 is the count rate at Jungfraujoch monitoring station during calibration.

d. Corrected neutron counts (N_{corr}) are calculated by multiplying the raw neutron counts (N_{raw}) by each of the correction factors:

$$N_{corr} = N_{raw} F_p F_Q F_C . \tag{4}$$

Unlike the COSMOS network in the United States, no adjustment is currently made to account for the detection sensitivity between individual CRS units (i.e. the individual CRS variation in sensitivity due to manufacturing tolerances etc.). Hence corrected neutron counts should not be compared equivalently between COSMOS-UK sites. However, these differences are implicitly accounted for in the soil moisture field calibration. In the future, a sensor-specific sensitivity factor will be provided following comparison of each CRS probe with a reference CRS unit at a standard location.

3. The corrected neutron counts are averaged up to (i) a 6-h running mean (based on the previous 6 h and available hourly) and (ii) 24-h block averages (available daily). It is recommended that 6-h or 24-h soil moisture data are used to reduce the noise associated with the cosmic-ray technique, particularly for UK conditions (Section 2.2). The corrected neutron counts are converted to volumetric soil moisture,

$$\theta_v = \theta_g \frac{\rho_{bd}}{\rho_w} = \left(\frac{a_0}{\left(\frac{N_{corr}}{N_0} - a_1 \right)} - a_2 - (\tau + SOC) \right) \frac{\rho_{bd}}{\rho_w} \tag{5}$$

where a_0, a_1 and a_2 are conversion coefficients with the values 0.0808, 0.372 and 0.115, respectively (Desilets *et al.*, 2010), θ_v is the volumetric soil moisture [m^3 m^{-3}], θ_g the gravimetric soil moisture [g g^{-1}], ρ_{bd} the dry bulk density [g cm^{-3}], ρ_w the density of liquid water (≈1 g cm^{-3}), τ the fraction of lattice and bound water [g g^{-1}] and SOC the soil organic carbon [g g^{-1}]. N_0 is found by rearranging this equation and inserting the soil moisture value obtained from the field calibration (Section 2.4) and the corrected neutron count rate observed during calibration.

The number of fast neutrons detected by a CRS probe at the surface decays non-linearly with depth in the soil (the rate of decay increases with increasing SM), i.e. most of the measured signal comes from the near-surface of the soil, whilst there is still a finite influence of deeper soil layers (Zreda *et al.*, 2008). The effective measurement depth (z*, cm) is defined as the soil depth above which 86% of the measured neutron counts are expected to have originated and is calculated according to (Franz *et al.*, 2013),

$$z^* = \frac{5.8}{\theta_v + \frac{\rho_{bd}}{\rho_w}(\tau + SOC) + 0.0829}\,. \tag{6}$$

2.4 Calibration of the cosmic-ray soil moisture sensor

An independent measurement of the average value of soil moisture in the CRS footprint is required for its calibration (Section 2.3). The first part of this procedure entails taking field soil samples; the second part comprises laboratory sample analysis. The field soil sampling procedure adopted follows Franz (2012) and Zreda *et al.* (2012) and therefore only brief details are presented herein.

Soil samples for volumetric soil moisture and bulk density determination are taken from 18 locations centred on the CRS probe: in each of six compass directions (0°, 60°, 120°, 180°, 240° and 300°) and at each of three distances (25, 75 and 200 m) from the probe. These samples are equally weighted due to exponentially declining sensitivity with distance from the probe. The exact sampling location can be varied somewhat to ensure that it is representative of the nearby area. At each location, samples are taken from six depths covering 0 to 30 cm below ground level, in progressive 5 cm increments. This procedure gives a target total of 108 samples, although it may not be practical at all sites depending on soil thickness and accessibility of sampling points. The soil samples are taken using standard 50 mm internal diameter, 51 mm length, sample rings (Eijkelkamp, Giesbeek, The Netherlands), giving a volume of 100 cm^3. Having removed any surface vegetation and augered to the appropriate starting depth, the rings are inserted in the vertical orientation using a closed ring holder (Eijkelkamp kit 07.53.SC). The samples are then transferred to sealed plastic bags and returned to the laboratory for analysis, where the initial mass of each sample is recorded. The samples are oven dried at 105°C for 36 hours and the mass recorded again allowing volumetric soil moisture and dry bulk density to be calculated (e.g. Gardner, 1986). Analysis of sample soil moisture variation with depth allows the depth-averaged value which most closely corresponds to the estimated probe effective depth at the time of sampling to be identified. This value is then used as the reference volumetric soil moisture content for calibration. Soil samples for the determination of lattice and bound water and soil organic carbon were taken following the sampling procedure outlined in Franz (2012). For further details see Blake (2015).

2.5 Additional extended time-series soil moisture data

CRS-1000/B probes have been deployed at the CHIMN and SHEEP sites since late 2011. In late 2013 these sites were upgraded to the COSMOS-UK station specification (Section 2.2). The same CRS probes were kept at each site, so that the calibration can be applied retrospectively. As far as possible, data were processed analogously to the procedure outlined above (Section 2.3), although there were some differences in the instrumental setup. The CRS probes were initially deployed with their own data loggers (Hydroinnova) and data were collected at hourly intervals, although not on the hour. Neutron counts were adjusted to give data on the hour by linear interpolation. The required meteorological data for correction of neutron counts were provided by a nearby station in Swindon, Wiltshire (20-30 km from the sites, Ward *et al.* (2013)). Hourly p and Q were adjusted to provide more appropriate values for each site, based on linear regression of concurrent data (03 October 2013/24 October 2013 to 31 January 2014 for CHIMN/SHEEP). The historical data from these sites has been merged with the current COSMOS-UK data stream, yielding a long time series of soil moisture extending back to 2011. CRS data were removed from both sites during snowy periods (05-06 and 10-12 Feb 2012, 18-26 Jan 2013), from CHIMN for one spuriously high SM reading concurrent with surface-water ponding (06 Jan 2014) and from the SHEEP dataset during summer 2013 when there was a suspected probe fault. Results from these two sites are presented in Section 4.1.

3 Cosmic-ray soil moisture sensor correction factors for UK conditions

Figure 3 shows raw neutron counts (N_{raw}) and the correction factors applied to calculate the corrected counts (N_{corr}) for the CHIMN site. Most of the variation in the raw neutron counts closely follows changes in atmospheric pressure (Figure 3a, b), although inverted because the intensity of neutrons reaching the Earth's surface decreases when the pressure (air density) is greater (Rivera Villarreyes *et al.*, 2011; Zreda *et al.*, 2012). The UK climate is subject to large variations in pressure (almost 80 hPa in Figure 3b), making the pressure correction factor, F_p, the most significant, ranging from 0.76 to 1.32 in Figure 3b. By comparison, the pressure correction is less than about 10% for the Santa Rita site in Arizona presented in Zreda *et al.* (2012), see their Figure 11. Additionally, neutron count rates are comparatively low in the UK because much of the land is close to sea-level (whereas the Santa Rita site is at ≈ 990 m elevation). The humidity correction factor is small, varying between about 0.98 in winter and 1.04 in summer (Figure 3c). The intensity correction is also small (usually < 5%, but with occasional spikes) and increases slightly over the study period to account for the decline in background counts (Figure 3d). It is primarily the large magnitude of F_p which means that it is only after the correction factors have been applied that patterns in the count rate start to resemble patterns in soil moisture (Figure 3e). The shapes of these patterns are inverted between N_{corr} and calculated soil moisture because higher soil moisture reduces the neutron count.

4 Results

4.1 Results from the Chimney Meadows and Sheepdrove Organic Farm sites

Near-surface soil moisture derived using the cosmic-ray method is presented in Figure 4 for CHIMN (04 August 2011 to 31 May 2014) and SHEEP (26 November 2011 to 31 May 2014). Over this period, southern England experienced extremes in groundwater and soil moisture levels driven by a rainfall deficiency in 2011 through to spring 2012, followed by exceptionally wet weather during 2012 and in winter 2013/14. To give some context for the observed soil moisture, rainfall data and sunshine hours from CEH Wallingford Meteorological Station, Wallingford, Oxfordshire (30-40 km from the sites) are provided (Figure 4, Figure 5).

The persistently low rainfall in 2011 raised concerns over drought and water resources. A heat wave at the start of October 2011, followed by relatively warm temperatures for the time of year, further depleted soil moisture via evapotranspiration during autumn 2011 (to levels comparable with summer 2013, Figure 4a). Soil moisture remained fairly constant and below saturation (0.3-0.4 $m^3\ m^{-3}$) during winter 2011/12, until a noticeable drop, coinciding with warm sunny weather, occurred at the end of March 2012. This was followed by a significant sustained increase in soil moisture in April 2012, when 2-3 times the normal amount of rain fell (Figure 5) making this month the wettest April on record (Met Office, 2012). Another rapid decline in soil moisture at the end of May coincides with a run of clear-sky days without rain. This was the first extended sunshine and warm weather since March and promoted rapid development of vegetation; the energy input from solar radiation was large and evapotranspiration rates were high during this period. Summer 2012 was very wet (soil moisture exceeded 0.4 m^3 m^{-3} in July at CHIMN). Most of September 2012 was fairly dry and more sunny weather led to the observed reduction in soil moisture, which ended suddenly with heavy rain in late September. Wet weather continued through winter 2012/13. In summer 2013 the effect of warm dry spells is evident. Depletion of soil moisture coincides with periods of sunny weather but intense rain regularly replenishes soil moisture (e.g. late July and early September 2013). This effect is most evident in near-surface soil, as monitored by the CRS. Winter 2013/14 was exceptionally wet, through to February 2014 and many regions experienced flooding (Huntingford *et al.*, 2014). Soil moisture is noticeably higher during winter 2012/13 and 2013/14 than during 2011/12 most likely due to the very low rainfall in 2011. In March 2014, the surface began to dry out as summer approached and rapid depletion of soil moisture is again seen when solar radiative input is high. In 2012, the soil moisture is higher at the end of the year than at the start and there is little evidence of an annual cycle; 2013 follows a more typical seasonal pattern in this respect, with soil moisture depletion in the spring through to summer. These results confirm the ability of the CRS to monitor the near-surface soil moisture response to wetting and drying events at the daily and seasonal timescale for UK conditions.

The time series suggests that soil moisture is generally slightly lower at SHEEP than at CHIMN (the difference is 0.04 m^3 m^{-3} on average), more so when the soil is moist, such as during summer 2012, winter 2012/13 and winter 2013/14. Whilst SHEEP is elevated, with the water table some tens of metres below the surface, and has well-drained chalky soils, CHIMN is low-lying with clay soils (Table 1). The shallow water table at CHIMN likely impedes drainage during winter; some surface water ponding was observed in the station's camera images down-slope of the site (but still within the CRS footprint) in early January 2014. Since the CRS responds to all surface water (hydrogen), ponded water will increase the derived SM to values above saturation; and in that sense introduces an error into the SM measurement. These data have been removed here (Section 2.5) but detection of surface water may be useful as a measure of the total available water, if data can be interpreted correctly by hydrological models.

Since the effective measurement depth depends on soil moisture (Equation 6), it varies with time (Figure 4b). However, even over these contrasting years the variation in effective depth is reasonably small, with daily averages ranging from about 0.08 m (during the wettest conditions) to 0.17 m (in drier conditions). There is a seasonal (SM-dependent) bias because the measurement depth is deeper under drier conditions. This is not an uncommon characteristic of measurement techniques but should not be forgotten when interpreting data. The effective measurement depth is usually slightly shallower at CHIMN compared to SHEEP (the average difference is 0.01 m), reflecting the generally higher SM at CHIMN. Due to the wetter soils in the UK compared with many COSMOS sites in the US, these effective depths are much smaller than the value of 0.76 m suggested by Zreda *et al.* (2008) for dry soils, but comparable to the value of 0.12 m for wet soils. For ‘relatively wet’ soils in Wüstebach, Germany, the effective depth does not exceed 0.30 m (Bogena *et al.*, 2013).

The large footprint of CRS sensors facilitates comparison with remote sensing products and land-surface models representative of much larger scales than point measurements. A daily soil moisture index is available from the Advanced Scatterometer (ASCAT), which supersedes the ERS scatterometer (Wagner *et al.*, 1999). The ASCAT product is a dimensionless relative measure of soil moisture (the SM index), varying between 0 and 1 for the driest and wettest conditions, respectively (Brocca *et al.*, 2011). Data are representative of very near-surface soil moisture: 0.005-0.03 m soil depth (Brocca *et al.*, 2010). COSMOS-UK data are compared to the ASCAT product for the nearest pixel to each site on a 12.5-km grid

(Figure 6). The CRS data have also been scaled to give a soil moisture index, based on the minimum and maximum volumetric soil moisture content values during the study period.

In general, the ASCAT and CRS data capture the same temporal trends. There is particularly good agreement in the timing of SM variations from September to December 2013, when intense rainfall leads to sudden increases in SM. In winter 2012-13 and winter 2013-14, CRS and ASCAT SM indices are close to 1, whereas ASCAT does not capture the consistently low observed soil moisture in winter 2011/12. Overall, the ASCAT data exhibit larger fluctuations, which is to be expected given that the data are representative of very near-surface soil moisture. During summer (May 2012 and June-July 2013) there are some differences in timing between CRS and ASCAT data, which may be partly due to vegetation effects in the ASCAT data. For the period presented here, agreement between the techniques is better at SHEEP than CHIMN. This may be partly due to a greater amount of vegetation during summer at CHIMN (a hay meadow) compared to the short grass at SHEEP which is fairly continuously grazed, and how well each site represents the typical land cover for the whole ASCAT 12.5 km x 12.5 km pixel.

Modelled daily SM from the Joint UK Land Environment Simulator (JULES model, Best *et al.*, 2011; Clark *et al.*, 2011) is compared with the CRS data in Figure 7. Model (version 4.0) output was generated for the near-surface soil layer (0.10 m depth). The model was run in standalone mode with the meteorological forcing provided by the Climate Hydrology Ecology Support System (CHESS) driving data (daily data with a spatial resolution of 1 km; Robinson *et al.* (2016)). The daily meteorological data were further disaggregated within the model to provide a diurnal cycle. The soil hydraulic properties are based on Brooks and Corey (1964). Land cover of 100% C3 grass was assumed. Generally, the model captures the observed trends in SM reasonably well, particularly at CHIMN. There is remarkably good agreement between model and observations at CHIMN throughout the first half of 2012;

during wetter conditions in July and October-December 2012 the model underestimated the observations. At SHEEP, JULES consistently underestimates the CRS data, although wetting and drying trends are well matched. Model underestimation may be related to the soil saturated moisture content parameter, which acts as an upper limit. Extending this comparison over a longer period would be informative, but unfortunately the required driving meteorological data for JULES is currently only available up to the end of 2012. It is anticipated that comparisons between model output and observations at more prototype stations will be highly valuable for model diagnostics and development.

4.2 Winter 2013-14

Results from the four prototype COSMOS-UK sites are shown from 01 October 2013 to 31 May 2014 (Figure 8). This period covers the exceptionally wet and stormy weather during winter 2013/14 (Huntingford *et al.*, 2014; Met Office and Centre for Ecology and Hydrology, 2014) and the subsequent soil moisture depletion in spring 2014. The time series for WADDN and WYTH1 begin from their respective installation dates (04 and 22 November 2013, Table 1). The gap in the data from WYTH1 is due to loss of power in December 2013.

At all sites, the soil moisture is seen to respond to precipitation patterns, particularly the heavy rain at the end of December 2013 and dry periods in mid-April and mid-May 2014. For the period shown in Figure 8, SHEEP tends to have the driest soils and WYTH1 the wettest. The variability is large for WADDN and WYTH1, in accordance with expectations that wetter sites have lower neutron counts and thus higher associated uncertainties. At WADDN the relatively high maximum SM values may be due to surface water ponding associated with slow infiltration into the low permeability clay soil. This surface water would be integrated into the CRS soil moisture value. At WYTH1, the large peaks in the 6-h SM data are well above what would usually be expected at saturation and are probably due to a mixture of noise and the contribution of other water stores (e.g. intercepted water stored in the canopy) which lower the neutron counts. Intercepted water stored in the tree canopy, moisture in above-ground biomass and water trapped in the litter layer (Bogena *et al.*, 2013) potentially complicate the results for WYTH1 and may be partly responsible for the generally very high SM values obtained; this will be a subject of future study.

These initial results demonstrate the capability of the CRS sensors and the prototype COSMOS-UK stations to capture (i) the SM response to changing meteorological conditions at daily to yearly timescales and (ii) differences in SM between sites with similar weather but different soil types and land cover. The findings also suggest important areas for further research, both for the CRS technique in general (e.g. other hydrogen sources, surface water) and for the conditions typical of the UK and other similar environments.

5 Summary and outlook

Initial results from the four prototype COSMOS-UK sites demonstrate the response of the large area CRS SM measurement to precipitation and drying processes (drainage and evapotranspiration). The temporal trends in SM over weeks and months across these four sites, within 50 km of each other (and thus subject to similar weather) are correlated as would be expected from the climatic drivers. However, the detailed response of each site is different – there is clear variability in the SM dynamics, particularly at shorter timescales, and the absolute volumetric soil water content. These inter-site differences in soil moisture are likely due to the differences in soil characteristics and underlying geology and water table depth. This shows the importance of sampling a range of soils and geology even under very similar climatic conditions.

There may be site-specific influences on the performance of the CRS technique, for example differences in the effective depth of measurement, and perhaps some other as yet unknown influences. Further research is required to investigate and determine such factors. One or more prototype COSMOS-UK sites will be instrumented with a large array of point soil moisture sensors, to form a Test and Validation Site (TVS), analogous to the Santa Rita CRS site in the US (Franz *et al.*, 2012). The TVS will primarily provide independent SM data which is representative of the CRS footprint, and will enable fundamental research into the performance of the technique. There are key questions that will be addressed in this research, such as how well the effective depth and spatial footprint models work under real field conditions.

Comparison with the JULES 0.10 m SM layer shows excellent application to both model diagnostics and potential for data assimilation. For the first time in the UK, these CRS observations provide an appropriate scale of measurement of near-surface SM for comparison with such hydro-meteorological models. Similarly, there is good correlation between the ASCAT and CRS SM data, showing the value of the COSMOS-UK network in ground-truthing satellite remote-sensing SM products. Some specific issues related to satellite SM retrieval could be revealed by these comparisons, for example the influence of denser/taller vegetation in mid-summer at CHIMN versus SHEEP. Sampling these different land management practices by the future deployment of more COSMOS-UK stations would provide a wealth of detailed information as to the performance of satellite SM retrievals under specific land surface conditions, as well as fundamental information on SM variability and underlying controlling processes across the UK. However, there is still a scale mismatch between the 12.5 km grid of the ASCAT data, as well as between the measurement depths, so great care must be taken in interpreting these comparisons.

Work by Franz *et al.* (2015) shows how static CRS measurements may be combined with a cosmic-ray rover, to produce high-resolution (1 km) SM maps. Spatial surveys over large areas (e.g. 12 x 12 km or more) are used to fit regressions between the infrequently rover-surveyed points and the temporally continuous but spatially static CRS measurements. The combination gives 8-hourly SM maps over the calibrated grid. Such techniques are likely to become even more cost-effective when rovers are deployed on autonomous robotic farm vehicles, which can enable much longer or continuous field survey periods with little labour cost. Subject to vehicle power charging and instrument security, these robotic vehicles could travel over hundreds of kilometres per day, every day, greatly increasing spatiotemporal resolution for SM mapping.

Future COSMOS-UK stations should be located on land cover and soil types representative of the surrounding local (≈5 km) area. Nevertheless, as new higher spatial resolution satellite SM products become available, these ground-truth comparisons will be spatially better matched. It is planned that some satellite SM products may even be at a finer resolution the CRS SM measurement. In these cases the planned TVS will be of great value internationally for comparison with new very high spatial resolution SM products.

The potential to measure snow accumulation has been recognised, and this will further develop with the deployment of the 'Snow Fox' buried CRS capsules at more northerly/higher altitude UK sites where significant snow accumulations are expected. It should also be noted that the soil moisture time series may need adjustment for the effect of lying snow.

It is planned to develop a COSMOS-UK network over the coming years (subject to funding) to sample more of the UK, with the goal of providing sufficiently dense coverage to generate a gridded UK SM map at fine spatial resolution (1 km^2) using interpolation and incorporation of satellite SM products. This will be a truly major advance in UK hydro-meteorological science, which will impact water resources management, flood forecasting, weather and climate modelling, farming, greenhouse-gas modelling and many other practical applications.

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Table 1 Characteristics of the four prototype stations, including soil organic carbon (SOC), lattice and bound water (τ) and bulk density (ρ_{bd}). The installation dates in parentheses give the date of initial CRS deployment at Chimney Meadows and Sheepdrove Organic Farm.

	CHIMN	SHEEP	WADDN	WYTH1
Site Name	Chimney Meadows	Sheepdrove Organic Farm	Waddesdon Manor	Wytham Woods
Latitude	51.71	51.53	51.84	51.78
Longitude	-1.48	-1.48	-0.95	-1.34
Altitude [m]	66	183	90	124
Soil type	Deep clay to sandy loam	Shallow chalky, silty loam with flints	Deep clay to loam	Intermediate depth loam to clay
Geology	Alluvium over Kellaways Formation and Oxford Clay Formation (Undifferentiated)	White Chalk Subgroup	West Walton Formation, Ampthill Clay Formation and Kimmeridge Clay Formation (Undifferentiated)	Kellaways Formation and Oxford Clay Formation (Undifferentiated)
SOC [g g^{-1}]	0.027	0.059	0.034	0.028
ρ_{bd} [g cm^{-3}]	1.30	1.03	0.98	0.95
τ [g g^{-1}]	0.050	0.031	0.021	0.017
Land cover	Grassland	Grassland	Grassland	Deciduous woodland
Date of installation	03 Oct 2013 (04 Aug 2011)	24 Oct 2013 (26 Nov 2011)	04 Nov 2013	22 Nov 2013

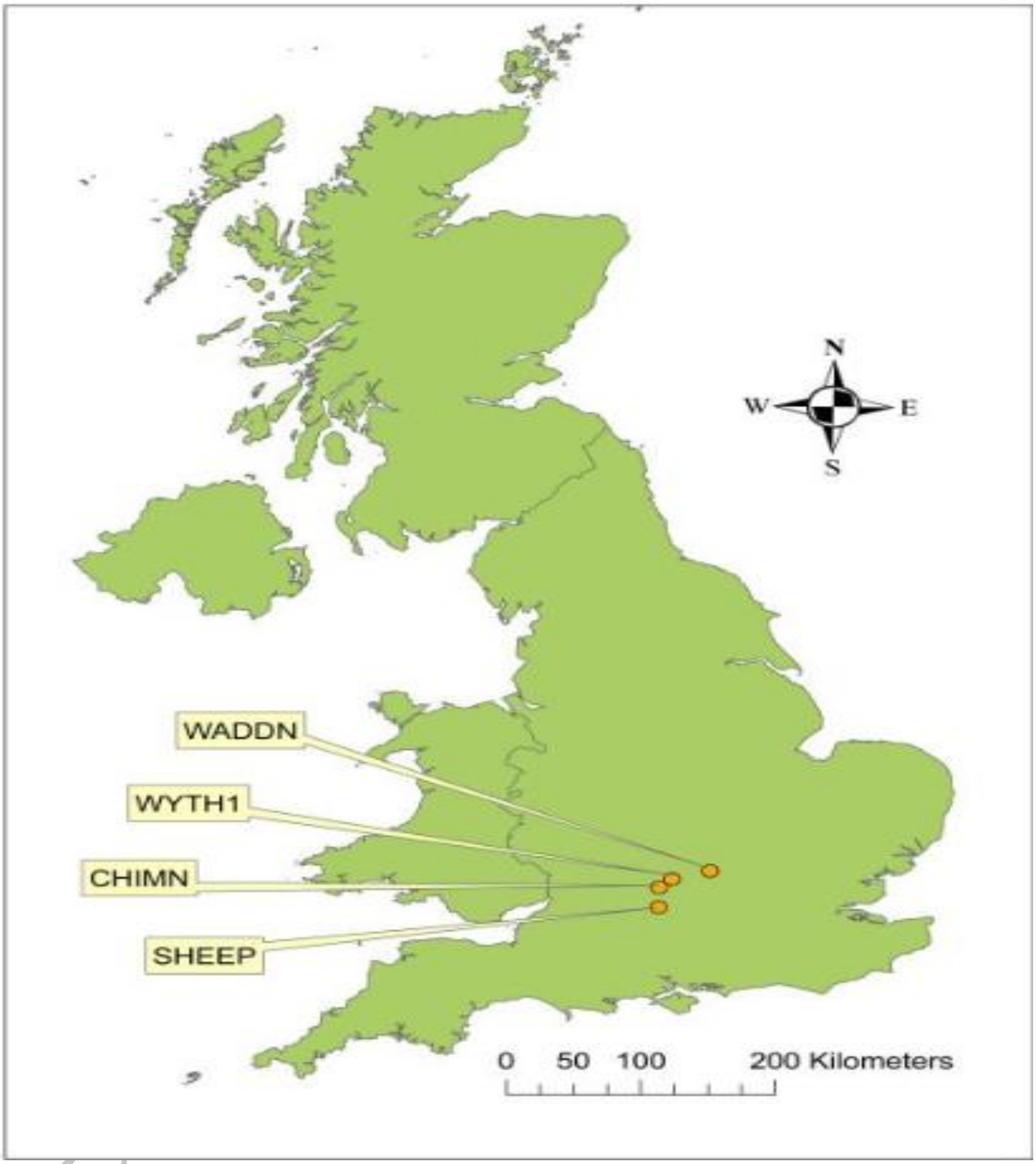

Figure 1 Locations of the four prototype COSMOS-UK stations at Chimney Meadows (CHIMN), Sheepdrove Organic Farm (SHEEP), Waddesdon Manor (WADDN) and Wytham Woods (WYTH1).

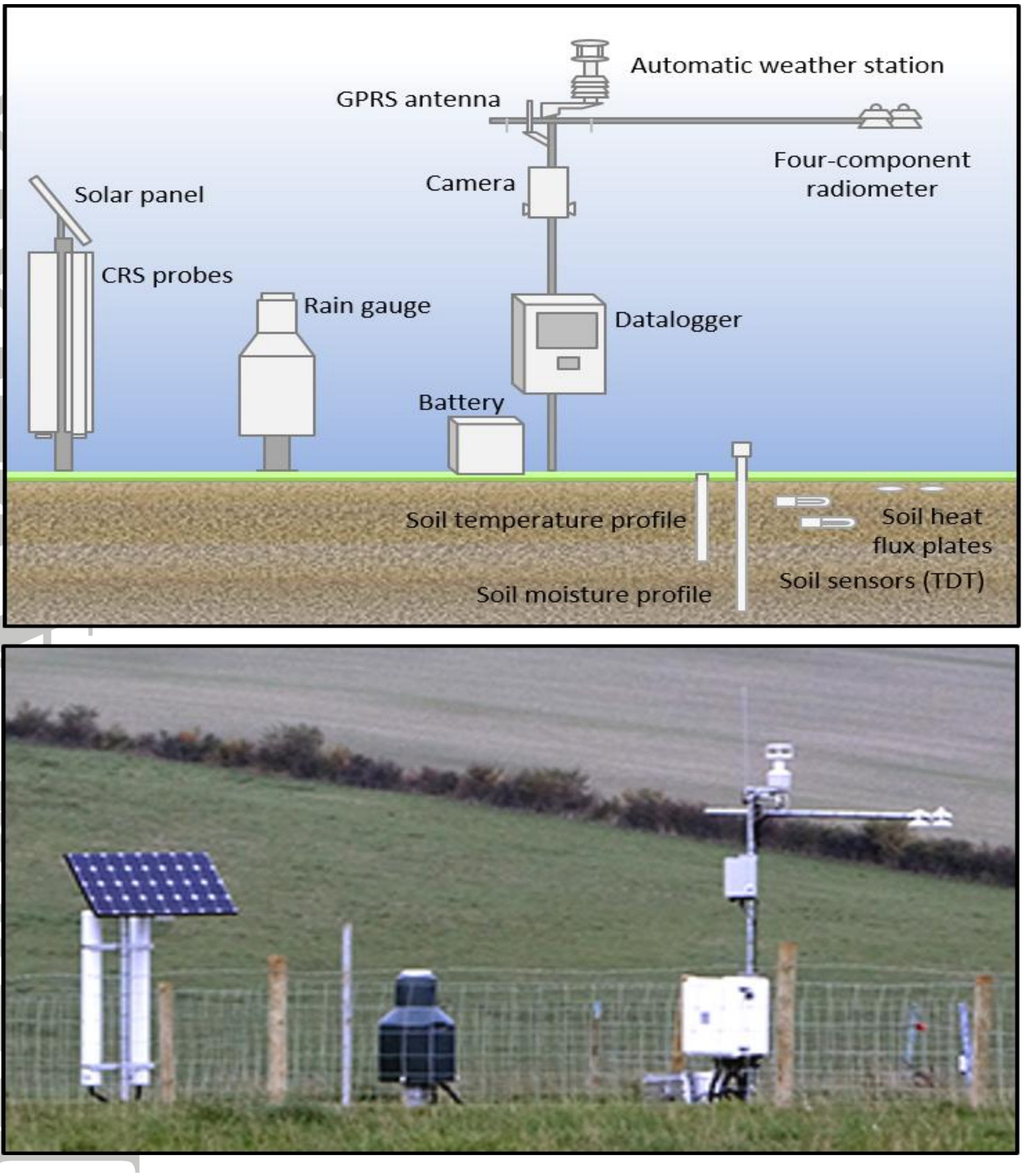

Figure 2 Diagram of the sensor layout for the prototype COSMOS-UK stations and photograph of the Sheepdrove Organic Farm site.

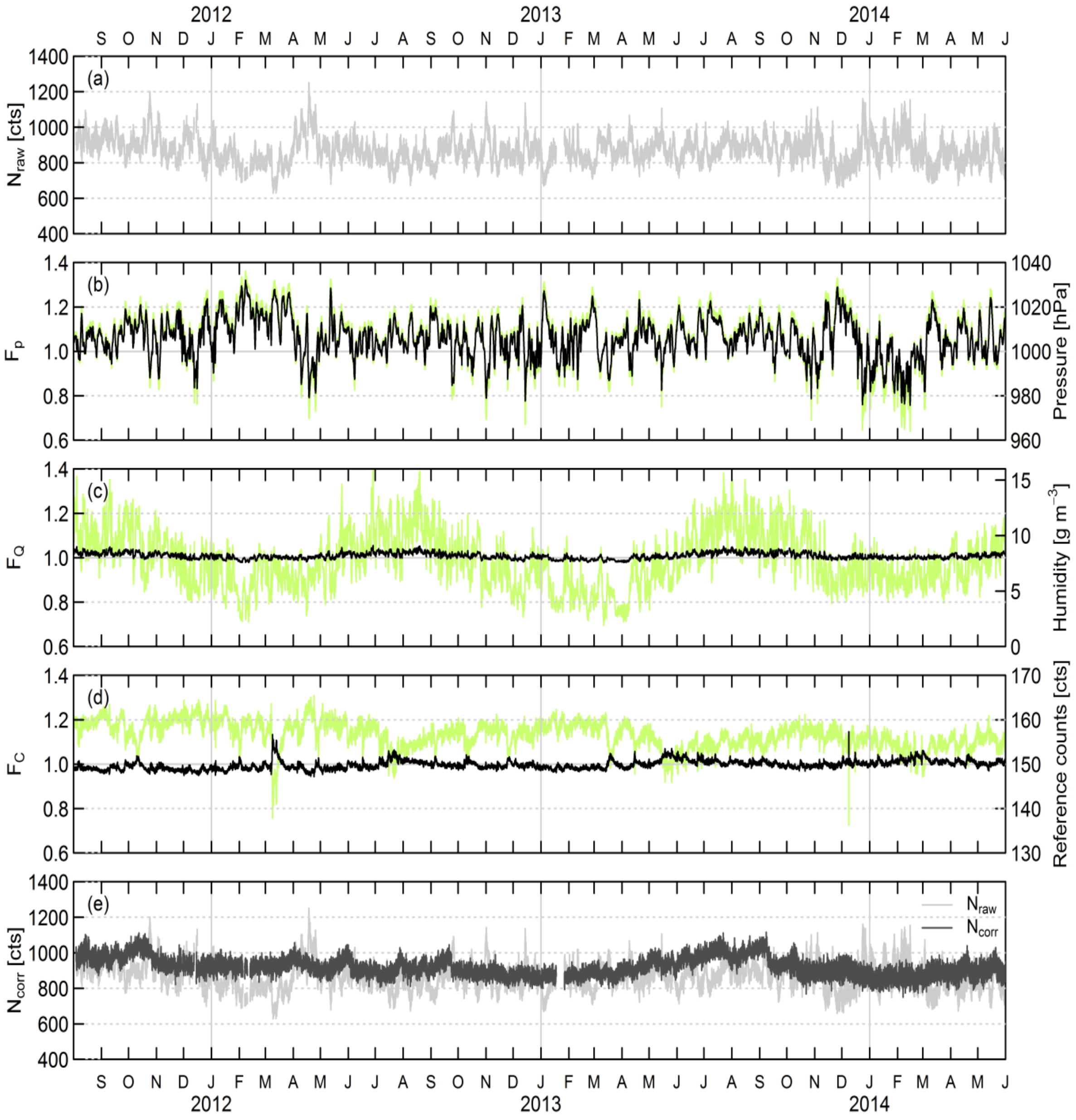

Figure 3 Raw neutron counts (N_{raw}) and the correction factors applied (F_p, F_Q, F_C, black lines) to obtain corrected counts (N_{corr}) for CHIMN. Relevant variables (p, Q, C) are also shown in each case (green lines, right-hand axes). The temporal resolution of the data is 60 min.

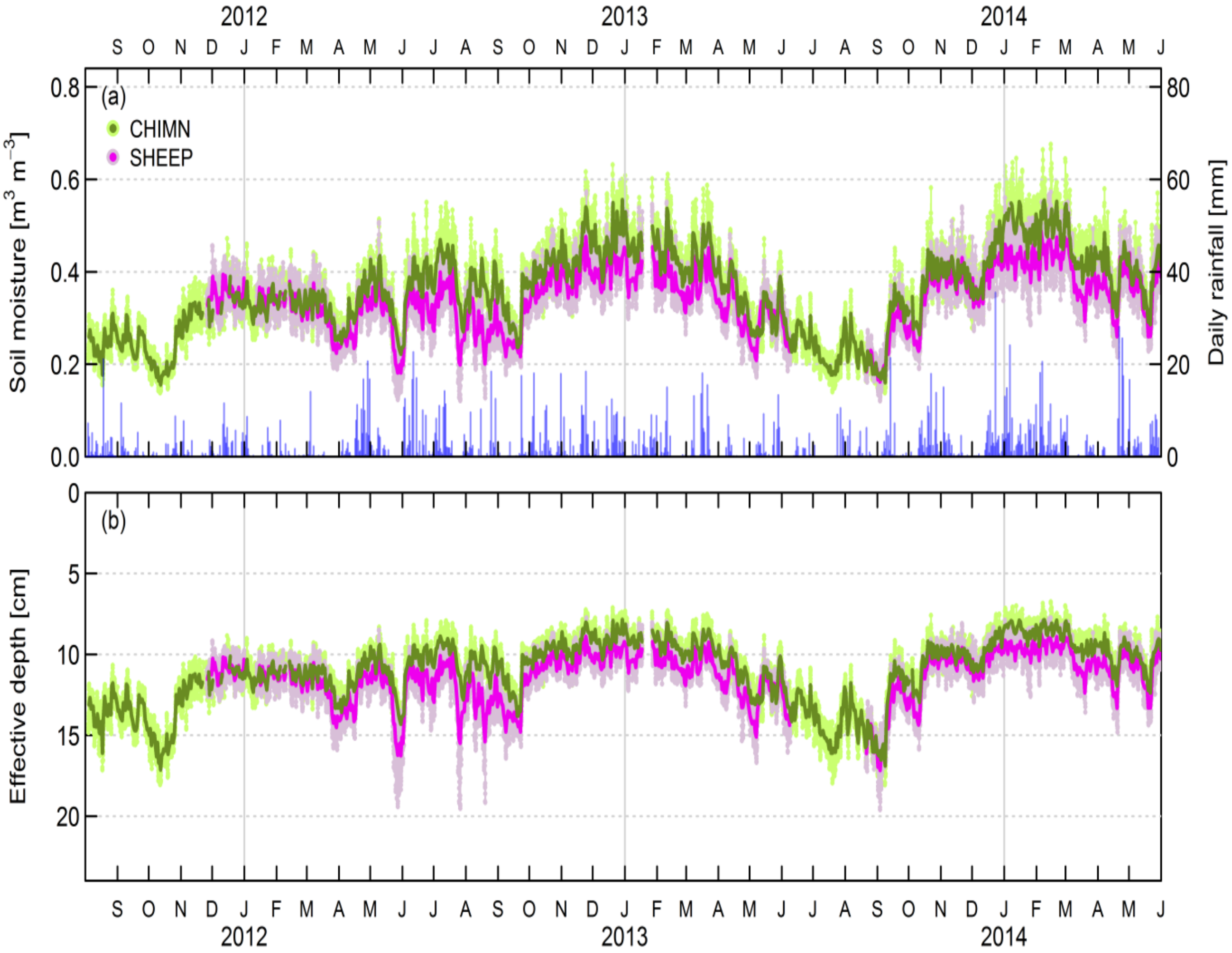

Figure 4 Daily averages (lines) and 6-h running means (shading) of (a) CRS soil moisture and (b) effective measurement depth for the two long-running COSMOS sites in the UK, CHIMN and SHEEP. In (a) daily rainfall from Wallingford, Oxfordshire is also shown (bars, right-hand axis).

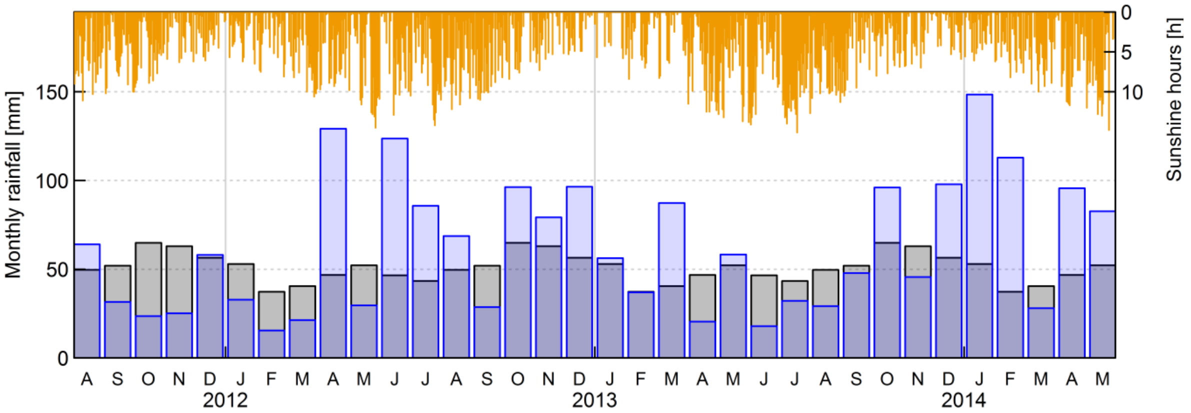

Figure 5 Monthly rainfall for the study period (blue) compared to 1980-2010 normal rainfall (grey) at Wallingford, Oxfordshire. Sunshine hours (daily) are indicated by the bars at the top (right-hand axis).

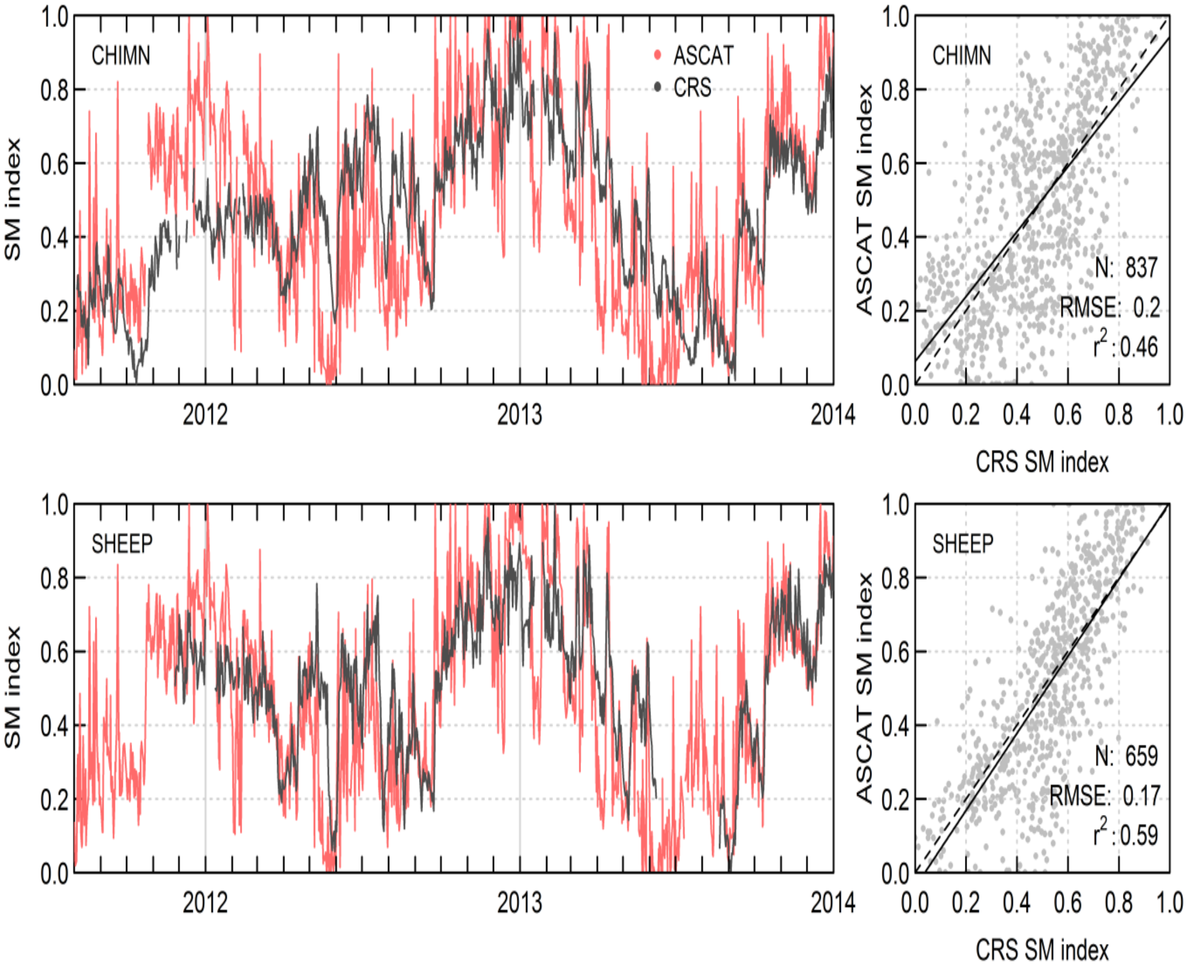

Figure 6 Comparison of soil moisture indices from CRS probes and ASCAT data for Chimney Meadows and Sheepdrove Organic Farm (August 2011-December 2013). The resolution of the data is daily. Dashed lines are 1:1; solid lines are linear regressions through the data.

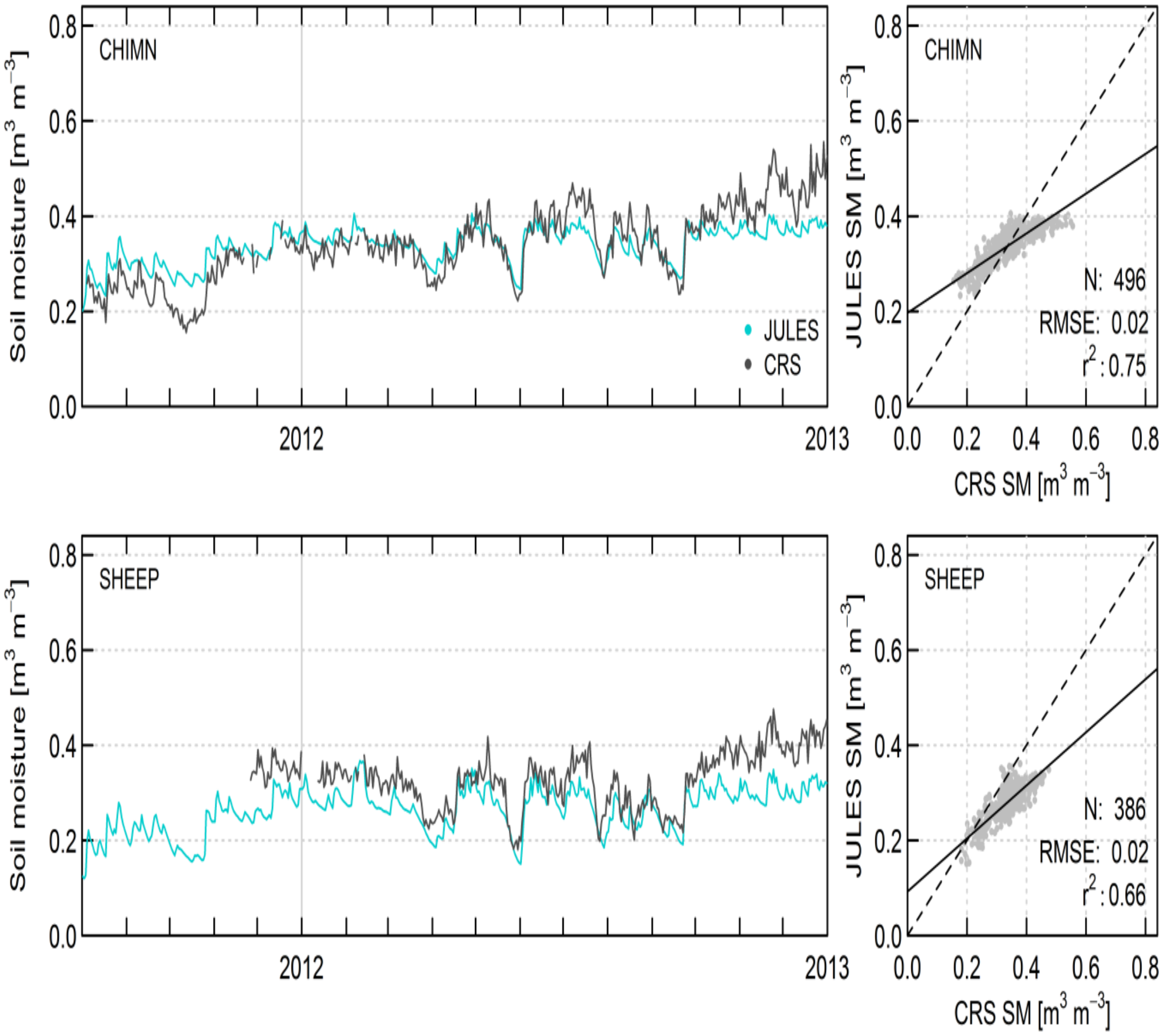

Figure 7 Comparison of volumetric soil moisture from CRS probes and the JULES model for Chimney Meadows and Sheepdrove Organic Farm (August 2011-December 2012). The resolution of the data is daily. Dashed lines are 1:1; solid lines are linear regressions through the data.

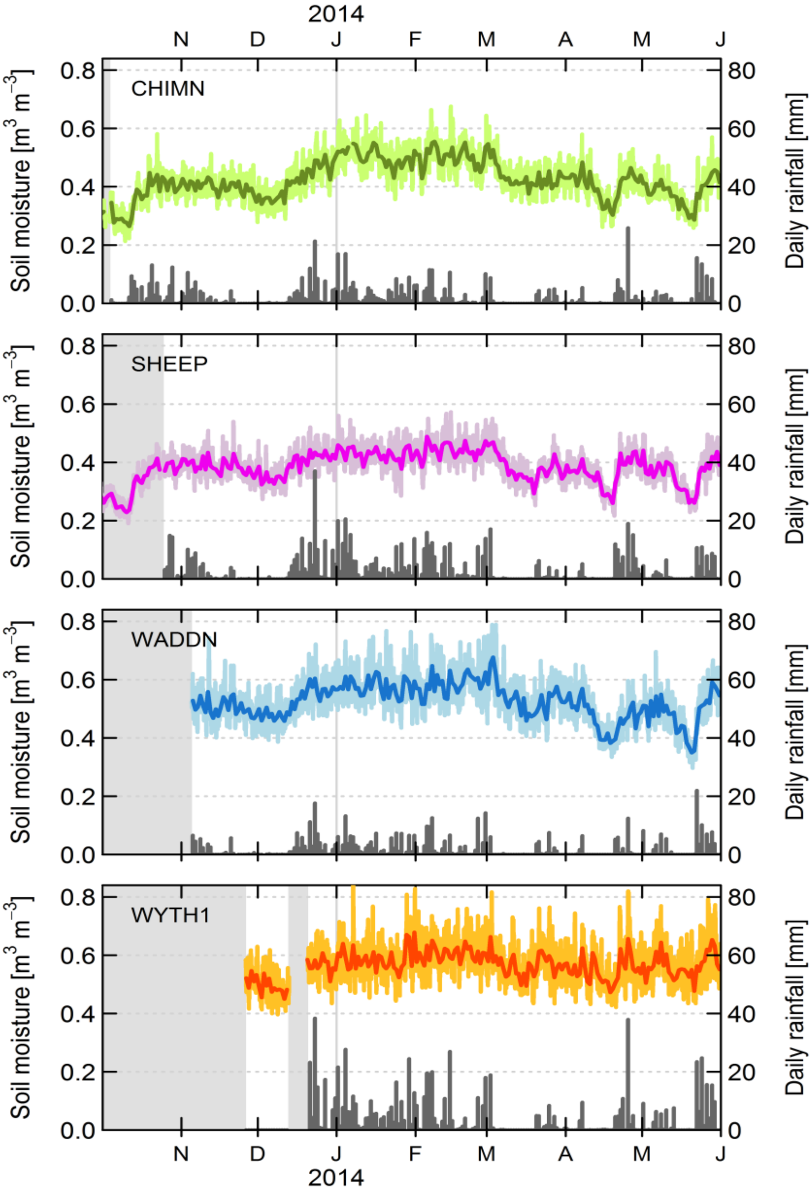

Figure 8 Daily averages (coloured lines) and 6-h running means (shading) of CRS soil moisture and daily rainfall (bars, right-hand axes) for the first four COSMOS-UK sites. Grey shading indicates missing rainfall data.