International Journal of Greenhouse Gas Control 53 (2016) 11–17

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

Carbon Capture and Storage (CCS) pipeline operating temperature effects on UK soils: The first empirical data

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ARTICLE INFO

Article history:
Received 12 April 2016
Received in revised form 18 July 2016
Accepted 18 July 2016

Keywords:
Carbon Capture and Storage
Transportation pipelines
Pipeline operating temperatures
Soil temperature
Soil moisture content

ABSTRACT

This paper presents the first empirical data of soil temperature and soil moisture profiles with depth in the context of a buried Carbon Capture and Storage transportation pipeline operating at higher than ambient soil temperatures. In an experimental approach, soil temperature responses are non-linear and are raised and restricted to within 45 cm of the subsurface heat source (hypothetical pipeline). A surface heat source is included to investigate interactions of natural seasonal surface heating of soils with subsurface heat. There is no interaction between subsurface and surface heat sources in the experimental system. Soil moisture profiles vary with soil type, with overall soil moisture losses of >10% over experimental time courses. Modelled soil temperature profiles show that the ability of soils to buffer thermal movement from depths up to 1.2 m from the surface is currently inadequately represented. Measurements provide the first elementary data of soil temperature changes resulting from a subsurface heat source for more accurate modelling of soil/pipeline interactions.

1. Introduction

Carbon Capture and Storage (CCS) is currently regarded as a critical mitigation strategy for the global reduction of the atmospheric greenhouse gas carbon dioxide (CO_2). It is reported as being capable of providing 19% of global CO_2 emission reductions by 2050 to facilitate a smooth transition to sustainable energy production and use (L'Orange Seigo et al., 2014). The UK Government is committed under the Climate Change Act, 2008 (http://www.legislation.gov.uk/ukpga/2008/27/contents) to reduce carbon emissions by 80% of 1990s levels by 2050. Globally, large scale CCS projects are still currently at proof of concept or FEED (Front End Engineering Design) stages, with only one, the SaskPower Boundary Dam Project, Saskatchewan, Canada being fully operational. The Global CCS Institute (http://www.globalccsinstitute.com/) has called for international and interdisciplinary collaboration to efficiently and swiftly engage in knowledge share of project design, construction, and operational experience whereby industry best practice guidelines and international standards can be adopted from the outset.

Many high CO_2 emitting industries (e.g. power stations etc.) in the UK are far from storage sites (offshore marine reservoirs) and therefore a technologically innovative infrastructure for CO_2 transportation must be initiated to carry CO_2 to safe storage. One area to be considered for the deployment of CCS across the UK is the operating temperature of the pipelines carrying dense phase CO_2 and the effects of this on the soils of agricultural, natural or other land use types lying above the pipelines as part of an environmental impact assessment.

Operating pipeline temperatures (T_{OP}) are set to optimise the mass to volume ratio of CO_2 carried in dense phase. The typical range of pressures and temperatures to ensure stability of a single-phase flow are between 85 and 150 barg, and could be between 13 °C and 44 °C; higher pressures maintain flow rates but incur higher operating temperatures (Leung et al., 2014). These physical constraints, also dependent on the CO_2 source (coal, gas, biomass), constitute part of the overall challenge to deliver efficient and economically viable transportation processes. As an integrated system, design and cost of capture and cooling of CO_2 prior to transportation at each emitting plant is likely to be a significant investment, it is therefore in the interests of industry, policy makers and stakeholders to quantify the full effects of pipeline operating temperatures and the impacts on pipeline design. Furthermore, the successful deployment of large scale CCS capability will depend not only on technical aspects, but also on social processes, i.e. government leadership and public perception and acceptance of potential impacts (L'Orange Seigo et al., 2014).

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http://dx.doi.org/10.1016/j.ijggc.2016.07.027

The soil environment comprises of geological physical components, which are subject to physical properties and laws, but also a biological component which affects and is affected by those physical properties. As an organic environment it is considered to be an ecosystem and provides ecosystem services (food production, water supply and purification, nutrient cycling, waste disposal, amenity and leisure) (Daily et al., 1997). Public and stakeholder support for CCS will, in part, depend on the knowledge of potential impacts on and continued maintenance of those ecosystem services. In the UK land use is intensive, with the majority of rural land being utilised agriculturally and as such is considered an important national industry in itself. Changes to soil temperature (T_{soil}) along the length of proposed pipelines for CO_2 transportation and at a depth encompassing the rooting zone of crops and other vegetation (~1 m from the soil surface) could potentially impact on soil health and crop yield. It is necessary therefore, to assess any potential environmental impact of higher T_{OP}.

T_{OP} was previously thought to be governed by the temperature of the surrounding soil. In high northern latitudes, T_{soil} varies from a few degrees below zero in the winter to 6–8.8 °C in summer, while in tropical locations, the soil temperature may reach up to 20.8 °C (Skovholt, 1993). In the UK, T_{soil} varies seasonally to both these limits. However, soil has the capacity to buffer physical attributes from rapid change. Used in a pH dependent context, “soil buffering capacity” avoids extremes of acidity and alkalinity by adsorption and release of chemicals which maintain the soil matrix within a range of pH values (Hajnos, 2014). By analogy, soil has the potential to “buffer” extremes of water holding capacity and temperature, depending on structural attributes (organic content, soil particle size, soil pore space). These buffering capabilities resulting from a heat source buried at ~1 m in soil are currently unknown.

In the absence of empirical data to test modelling proficiency to predict accurate temperature profiles ($T_{profiles}$) resulting from a buried heat source and subsequent effects on water distribution at depth, we set out to produce the first data generated in a laboratory based experimental system. The aim of the study was to measure the extent of thermal movement through a soil column and derive a value for potential thermal buffering capacity (T_{pbc}) resulting from a subsurface heat source. It was not the aim to replicate natural conditions or to test complex soil models, which is beyond the scope of this study.

A laboratory experimental system was designed to produce a subsurface heat source below a soil column that would be stationed within a constant temperature to allow measurement of heat transfer up through the soil column over time. The design was not meant to replicate outdoor conditions, but rather to investigate the fundamental nature of heat transfer from below and the ability of soil to buffer thermal input at depth in the context of potential impacts on the biological component of the soil environment. Two soil types representing a loam based organic and a loamy-sand mineral soil were measured under dry, then wet conditions. A range of hypothetical pipeline operating temperatures were tested at 43 °C, 35 °C, 33 °C and 27 °C; ~40 °C was considered the worst case scenario operating temperature of a dense phase CO_2 transportation pipeline. Soil moisture was also measured at 4 points along the height of the soil column. Moisture content was measured after thorough mixing of the soil at the beginning of each experiment (dry soil) and then with water added to approximate reported field capacity values for the soil type to represent wet soil (Delta-T HH2 user manual v 4.0.1 (http://www.delta-t.co.uk/). Field capacity is defined as the water holding capacity of soil following cessation of natural drainage (Vanderlinden and Giraldez, 2014). All experiments were carried out under constant ambient air temperature (T_{amb}) in a controlled environment which was maintained throughout to avoid compounding variables, such as fluctuating air temperatures, in order to derive a value for potential thermal buffering capacity (T_{pbc}) resulting from a subsurface heat source at shallow depth in the soil.

2. Materials and methods

2.1. Experimental

A frame to hold a solid aluminium sheet (L550 × W550 × H 20 mm) was constructed of Dexion™ framing. A laboratory hotplate (300 × 500 mm, Stuart D500, SLS, UK) was raised via a scissor jack to make even contact for efficient heat transfer to the aluminium sheet (the subsurface heat source). The soil container (RPVC piping—outside diameter 495 mm, inside diameter 485 mm, height 950 mm) was placed directly onto the aluminium sheet and graduated in 50 or 100 mm lengths to enable soil levels to be determined and thermocouples (1 m length PTFE wire [K alloys; NiCr/NiAl] as a twisted pair with a welded bead and terminating in a moulded thermocouple plug; K-type, RS components, UK) were inserted every 100 mm throughout the depth to the centre of the soil column via drilled holes (5 mm diameter) in the soil container. Thermocouples were connected to a data logger (TC-08, Picotechnology, RS components, UK) and laptop, allowing the constant monitoring of 8 thermocouples at a time.

An additional heat source above the soil column to simulate sunlight heating was supplied by a halogen floodlight (bulb output 150 W, 140 × 100 × 140 mm, Rs type, Wickes, UK) over a surface area of 0.196 m^2 giving an irradiance of 0.75 kW m^{-2} (sunlight average is 1.36 kW m^{-2}). The spotlight was fixed 30 cm above the soil surface to give maximum spread of heat over the surface area of the soil column. Fig. 1 shows both a schematic of the experimental rig and the rig in situ. Experiments were carried out within a temperature controlled environment to standardise all other variables. Ambient air temperature was constant at 19.5 (±1.0) °C throughout.

Soil moisture was measured at 4 points along the height of the column with access for a soil moisture probe (ML3 probe, DeltaT, UK) on each side of the soil column. The probe was calibrated for each soil type using the non-clay method reported in the device manual. The probe was attached to a probe reader (HH2, DeltaT, UK, http://www.delta-t.co.uk/) and recorded manually over time, after which the access holes were sealed with tape. Water was added to approximate reported field capacity values after natural drainage as closely as possible for the soil type (organic loam ~26% and sandy mineral ~15%) (Vanderlinden and Giraldez, 2014).

John Innes no. 3 compost (widely available in the UK) was used as a standard uniform soil consisting of pre-mixed loam:peat:sand in a ratio of 7:3:2 by volume (here denoted organic soil type). The addition of 25% extra sand increased the mineral content and represented the denoted mineral soil type (more open structure, free-draining). As a uniform soil matrix, the study did not investigate constituent physical properties of different soil types. Thermal diffusivity was calculated as (Campbell and Norman, 1998):

$$\alpha = k/pc_p$$

where k = thermal conductivity (w m^{-1} K), p = bulk density (kg m^{-3}), c_p = specific heat capacity (J kg^{-1} K).

Soil bulk density for calculation of thermal diffusivity was measured as in Campbell and Norman (1998).

2.2. Modelling

The available experimental system (soil column depth of 850 mm) did not fully cover the proposed depth of a buried pipeline at 1200 mm (National Grid, UK—pers. comm.) from the upper surface of the pipeline to the soil surface, therefore empirically generated temperature profiles were incorporated into an exist-

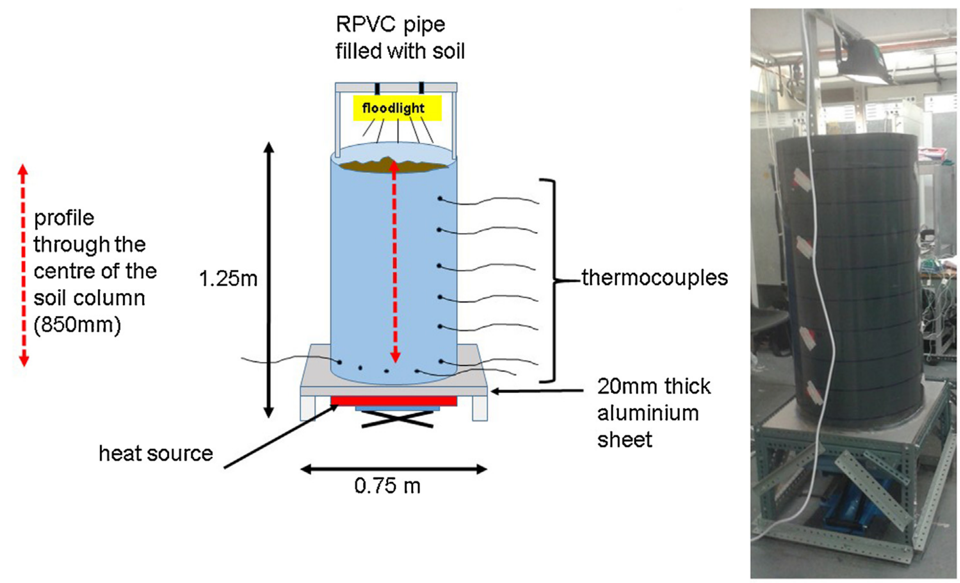

Fig. 1. Experimental design. Schematic design and in situ photograph of the experimental rig.

ing simple non-process climate-driven soil temperature model (Kusada and Archenbach, 1965) to produce empirically-derived modelled profiles from a 1200 mm pipeline depth to the surface; i.e. an additional 350 mm depth.

The original Kasuda-Archenbach (K-A) climate-driven soil temperature model was chosen for simplicity and was specifically designed to model temperature changes within the top 3 m (Kusada and Archenbach, 1965) of soil and was therefore suitable for this study. Output from the model is a single temperature profile from surface to depth which, when reversed from depth to surface, gives a suitable framework with which to compare the single thermal profiles measurements of the experiments and extend the depth required to that of a buried pipeline. We acknowledge that the model constitutes a one-dimensional diffusion equation, whereas the experimental system is not one-dimensional (heat loss at the sides of the soil column), however in respect of the potential effects on the biological components of soil, this would manifest as a temperature effect within the zone of interest and is therefore considered adequate for the present study. The model is described as:

$$T = T_{mean} - T_{amp} \times \exp\left[-\text{depth} \times \left(\pi/365/\alpha\right)^{0.5}\right] \times \cos\left\{2\pi/365 \times \left[t_{now} - t_{shift} - \text{depth}/2 \times \left(365/\pi/\alpha\right)^{0.5}\right]\right\}$$

where T = temperature (°C), T_{mean} = mean surface temperature (average air temperature) (°C), T_{amp} = amplitude of surface temperature (maximum air temperature minus minimum air temperature) (°C), depth = depth below the surface (m), α = thermal diffusivity of the ground (soil), t_{now} = current time (day), t_{shift} = day of the year of the minimum surface temperature.

The model was tested for accuracy against recorded climate and soil temperature data to depths of 100, 200 and 300 mm provided by Rothamstead Agricultural Research Station, UK. The model was used to derive (a) a top-down surface to depth heat profile (summer air temperature of 20 °C, year day 212), (b) a reversed bottom-up profile (with subsurface experimental temperatures set as air temperature) from depth to surface. These profiles were combined. Parameters used to model 'best fit' to empirical data are listed in Table 1.

Table 1
Parameters used to model 'best fit' to empirical data.

$T_{simulated}$ (°C)	T_{mean}	T_{amp}	T_{shift}	$\alpha_{calculated}$	Year day
43 (organic dry)	9.5	32	37	0.02974	212
43 (organic wet)	9.5	32	25	0.02186	212
33 (organic wet)	9.5	23	20	0.02186	212
27 (organic wet)	9.5	18	16	0.02186	212
35 (mineral dry)	9.5	25	20	0.03324	212
35 (mineral wet)	11	35	50	0.03246	212

3. Results and discussion

3.1. Soil temperature

At the start of each experiment, temperatures were even throughout the soil column, corresponding to T_{amb}. Increases in temperature up through the soil column were measured over time with an average time to reach constant temperature profiles of 17 h. Constant $T_{profile}$ set the time limit for each experiment. Soil $T_{profiles}$ from the subsurface heat source up through the soil column were generated for each experimental subsurface temperature and plotted as height above the heat source (Fig. 2a, Table 2). All profiles show that ~450 mm above the heat source, temperatures are close to or the same as T_{amb} and above 650 mm from the heat source, are close to or lower than T_{amb}. At 750 mm and above, temperature dips below T_{amb} due to evaporative cooling in the surface layers of the soil. Wet soils are slightly lower in temperature than equivalent dry soils between the heat source and ~350 mm above when compared at 43 °C and again when compared at 35 °C, regardless of organic or sandy mineral content (Table 2). Whilst it is recognised that soil properties and dynamics are complex, basic physical principles are simplified here for context. The general properties of soil that affect heat transfer are soil bulk density, the fraction of mineral to organic material and water content (volume fraction). All of these properties contribute to the volumetric heat capacity of a specific soil type. Thermal conductivity is also dependent on these properties, with evaporation and condensation within soil pores affecting a substantial quantity of heat transfer (Campbell and Norman, 1998), it can be expected therefore that more open sandy soils would have different thermal properties to compact silty/clay soils. Regardless of subsurface heat source initial temperature and soil type, all $T_{profiles}$ exhibit a non-linear response curve (Fig. 2a).

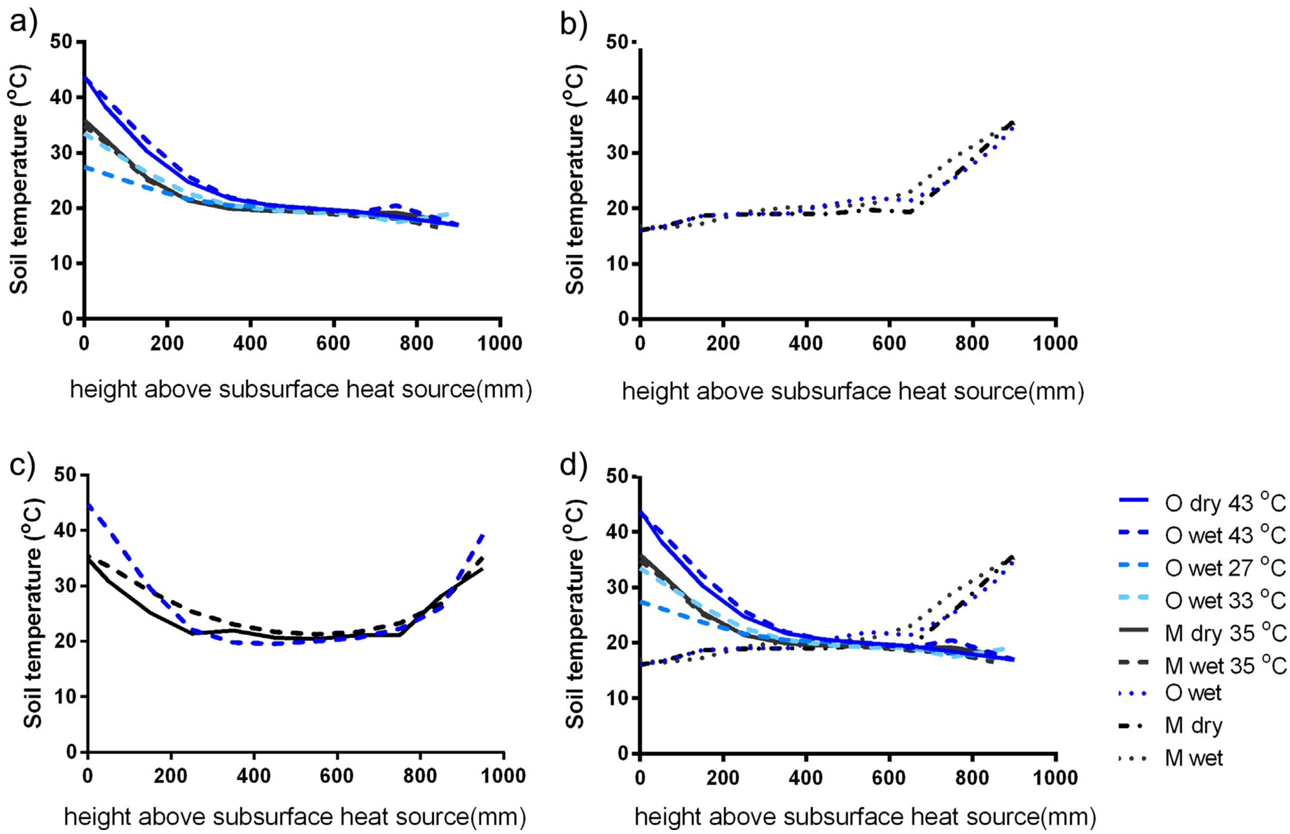

Fig. 2. Soil temperature profiles. (a) Soil temperature profiles from the subsurface heat source up through the soil column for each experimental temperature. (b) Soil temperature profiles from a surface heat source for three separate experiments. (c) Soil temperature profiles with simultaneous subsurface and surface heat sources in three experiments. (d) Combined profiles from subsurface and surface heat sources shown in (a) and (b) [O = organic, M = mineral, numeral = subsurface experimental temperature °C].

Table 2
Soil temperature profile data (°C) from 6 experiments. From subsurface heat source to soil surface through the centre of the soil column. Air temperature was constant at 19.5 °C (±0.5) [n/m = not measured].

Profile (mm)	Soil type					
	organic dry	organic wet	mineral dry	mineral wet	organic wet	organic wet
	Experimental subsurface temperature					
	43 °C		35 °C		33 °C	27 °C
0 (subsurface heat source)	43.8	43.5	36.1	35.0	33.5	27.2
50	38.8	40.0	33.6	32.9	31.0	26.2
150	31.4	32.2	27.7	27.1	26.5	23.7
250	25.8	25.7	23.1	22.6	22.6	21.7
350	22.4	22.0	20.9	20.6	20.5	20.5
450	21.0	20.5	20.0	19.7	19.6	20.2
550	20.3	19.9	19.4	19.4	19.2	20.0
650	19.7	19.1	19.4	18.8	19.1	n/m
750	18.5	17.6	19.2	17.3	17.5	n/m
850 (soil surface)	n/m	n/m	18.0	16.4	14.0	16.9

Three of the experiments, organic wet and mineral (wet and dry) were investigated using surface heating only (Fig. 2b) and then separately with surface heating in addition to subsurface heat (Fig. 2c). This was to simulate sunlight heating of the soil surface in summer months when T_{soil} can increase substantially and then to measure any interaction with subsurface heating in raising the overall $T_{profile}$. Temperatures of the soil surface are raised considerably (~15 °C) above ambient, with surface heat penetrating to a depth of 300 mm from the surface. The wet mineral soil shows higher overall heating in surface layers than either the wet organic or mineral dry soil (Fig. 2b). Fig. 2c shows the effect on $T_{profiles}$ when both heat sources are applied simultaneously to the soil column. There is a clear central zone whereby T_{soil} is unaffected by either heat source and therefore shows no interaction between heat sources. When all profiles are combined, this zone is still evident (Fig. 2d).

As the available experimental system (soil column depth of 850 mm) did not fully cover the proposed depth of a buried pipeline to 1200 mm, empirically generated temperature profiles were incorporated into a simple climate-driven soil temperature model (K-A) (Kusada and Archenbach, 1965) to produce empirically-derived modelled profiles from a 1200 mm pipeline depth to the surface. Fig. 3 shows modelled profiles as deviating from linear thermal gradients (see below) at 35 °C and 43 °C (assuming a summer UK air temperature of 20 °C as in controlled experimental conditions). Additionally, a T_{OP} of 20 °C was modelled as it could not be experimentally tested with a T_{amb} of 19.5 °C; 20 °C is considered

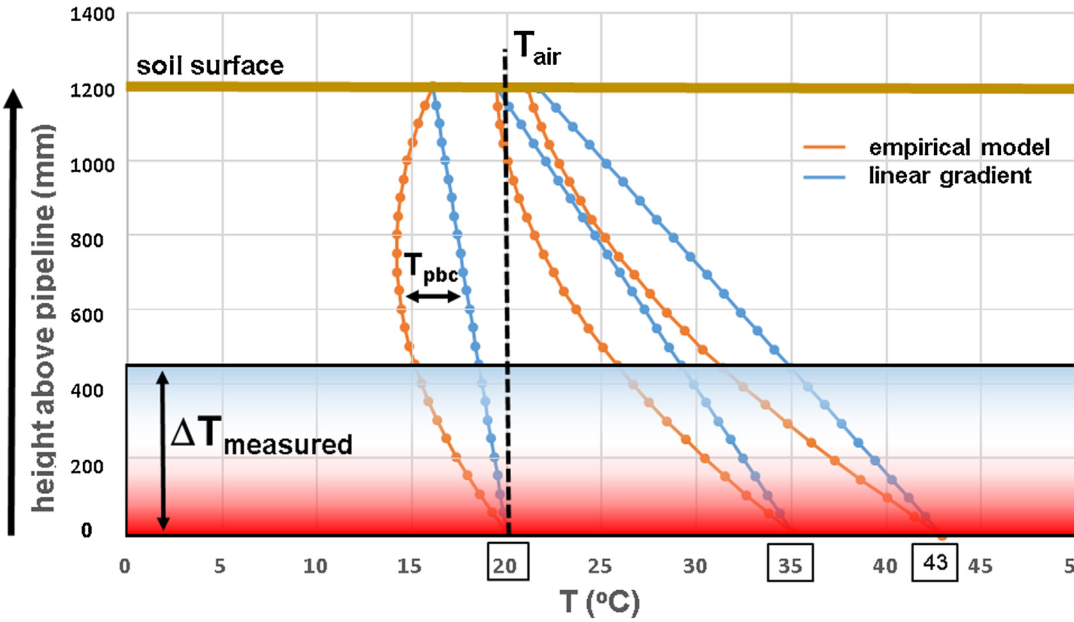

Fig. 3. Modelled temperature profiles to depth of 1200 mm. Modelled temperature profiles using empirical profile data in a climate-driven model (K-A) for two experimental (organic dry soil at 43 °C and mineral dry soil at 35 °C) and one predicted (organic dry soil at 20 °C) subsurface temperatures. Hypothetical linear temperature gradient from subsurface heat to modelled soil surface temperature for each experimental subsurface temperature [T_{pbc} = potential thermal buffering capacity, T_{air} = modelled air temperature at the soil surface, $\Delta T_{measured}$ = extent of depth of temperature change recorded in experiments with subsurface heat].

a potential *lower* limit of T_{OP} when other factors are considered (e.g. pipeline design and construction aspects, CO_2 sources etc.) and will be incorporated into modelled responses.

Deviation from a linear gradient calculated from an initial subsurface heat source temperature to empirically modelled soil surface temperature gives a derived value for T_{pbc} that is in addition to a physical thermal gradient expected over the given distance and represents the ability of these soils to buffer thermal movement and thus allows quantification of this effect. This is calculated as up to 4 °C cooler (Table 3). However with T_{OP} at 35 and 43 °C the model does not reduce soil temperature rapidly enough with distance to reflect experimental $T_{profiles}$ which measure 21 °C or less at 450 mm above the subsurface heat source and gives a difference of up to 12.6 °C cooler (Table 3). Clearly there is still an inadequacy in the model when using 'best fit' parameters (Table 1) to account for the full thermal buffering capabilities demonstrated experimentally. Furthermore, modelled responses do not replicate a central zone where temperature is unaffected by heat input, as in measured profiles. These results illustrate the importance of measured data to elucidate processes and refine modelling capabilities. Using empirical data alone, a calculated central zone unaffected by subsurface heat increases to a depth of 700 mm from the soil surface when the full distance to a hypothetical pipeline is 1200 mm. This depth comprises the majority of the rooting zone of most UK crops, and could therefore effectively negate pipeline operating temperature concerns with respect to impacts on vegetation growth. Surface heat (simulated sunlight, high air temperature) is a natural phenomenon to which all vegetation and soil biological components are adapted. As there was no evidence of interaction between surface and subsurface heat sources, there would be no potential additional effects of seasonal surface heat. It is noted that some heat loss from the soil column may have occurred through the wall of the soil container, but this would also be a natural phenomenon with respect to some lateral movement of heat away from the subsurface heat source in an open field system. Increased lateral heat movement in a fully open three-dimensional system would effectively reduce the thermal input at the both the centre of the experimental soil column and above a buried pipeline in a field location; as such the experimental results represent near maximum input of thermal heat to the soil column under experimental conditions. The cylindrical soil column, providing the least surface area to volume ratio, was pre-experimentally calibrated to a relatively high environmental temperature of 19.5 °C throughout. This temperature is higher than that recorded at one meter depth in UK soils (15.8 °C at 1000 mm under grass in August 2012; Rothmet data source); as a lower environmental temperature would create a greater thermal

Table 3
Difference between measured and modelled soil temperature at 450 mm above the subsurface heat source. Maximum deviation from a hypothetical linear temperature gradient from subsurface temperature to modelled surface temperature (at 1200 mm above heat source) giving a value for potential thermal buffering capacity (T_{pbc}) under experimental conditions [n/m = not measured, n/a = not applicable].

Soil type and subsurface experimental temperature (°C)	Measured temperature (°C)	Modelled temperature (°C)	Difference between measured and modelled temperature at 450 mm above heat source (°C)	Maximum deviation from hypothetical linear gradient temperature to modelled temperature (T_{pbc} – potential thermal buffering capacity °C)
Mineral (dry) 35 °C	19.5	26.6	−7.1	−2.6
Mineral (wet) 35 °C	19.6	25.2	−5.6	−4.0
Organic (dry) 43 °C	20.5	33.1	−12.6	−3.0
Organic (wet) 43 °C	20.5	31.5	−11.0	−4.0
Organic (dry) 20 °C	n/m	15.0	n/a	−3.5
Organic (wet) 20 °C	n/m	17.7	n/a	−0.8

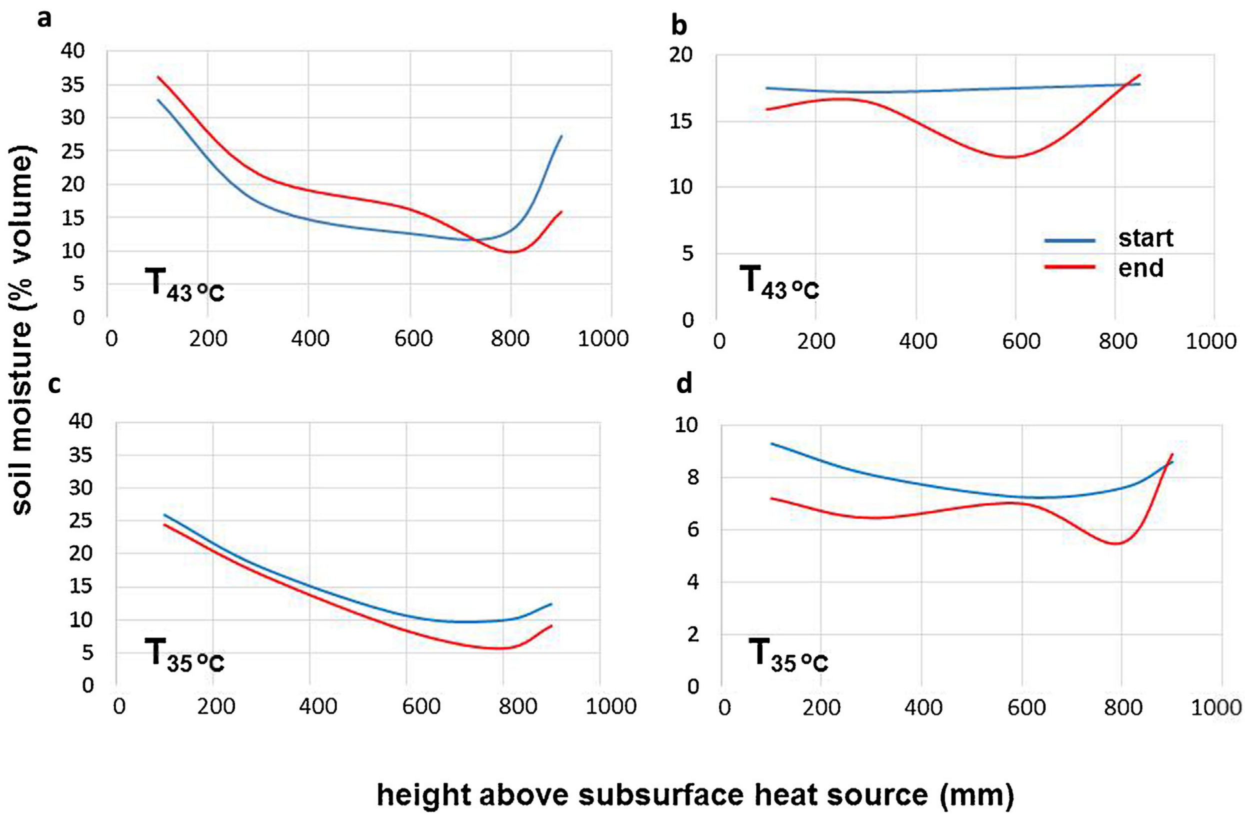

Fig. 4. Soil moisture profiles. % water content throughout the soil column at the start and end of each subsurface heat experiment. (a) organic wet (b) organic dry (c) mineral wet (d) mineral dry [$T_{(x)}$ = experimental subsurface heat temperature (°C)].

Table 4
Moisture content of soils at the beginning and end of each subsurface temperature experiment showing mean water content (% volume) for the whole soil column, the duration of the experiment, % loss from start value at the end and additional % loss with combined subsurface and surface heat sources where applicable [n/a = not applicable].

Experiment (soil type and subsurface temperature)	Mean moisture content of whole soil column (% volume water)		Experiment duration and % water loss from start values of the whole soil column			
	start	end	duration (h)	% water loss with subsurface heat	Additional % loss with surface heat	Total water loss (%) from start
Organic dry 43 °C	17.5	15.4	72	10	n/a	10
Organic wet 43 °C	29.0	24.4	11	16	n/a	16
Organic wet 33 °C	25.1	20.9	22	17	4	21
Organic wet 27 °C	23.5	18.5	23.5	21	n/a	21
Mineral dry 35 °C	8.2	7.3	22	11	3	14
Mineral wet 35 °C	16.0	16.0	23	0	16	16

gradient for lateral heat loss, therefore, heat loss from the sides of the soil container was minimised as much as possible, whilst still being capable of generating thermal gradients within the soil column. The results provide potential temperature profiles that would equate to a near maximum in a UK field setting.

3.2. Soil moisture

Effects of higher soil temperatures may potentially impact on vegetation through redistribution and loss of available water in the soil. Described simply, a gradient of the water potential is the driving force for liquid water movement in soil and arises from the attraction between water and soil particles. Adhesive and cohesive forces bind the water to soil particles and moisture characteristics are different for different soil types (Campbell and Norman, 1998). Most of the water in clay soil is held very tightly (at low potential) because the large surface area of clay binds the water. In sandy soil water is held loosely (at high potential) because the sand matrix is ineffective in binding water. When soils are saturated, their water potential is near zero, but gravity drains them to potentials corresponding to field capacity. Field capacity is used in an agricultural context as an approximate measure of available water for plant crops. As plants extract water, water potential decreases until all remaining water is so tightly held that roots are unable to access water further (Campbell and Norman, 1998) in the absence of additional rainfall or irrigation. This would impose a limit on plant growth.

Fig. 4 shows soil moisture profiles at the start and end of dry and wet soil experiments with a subsurface heat source at 43 and 35 °C (for both organic and mineral based soil types). Wet soils (Fig. 4a & c) show an even loss of water up through the soil column until near surface levels, and profiles are similar at both the start and end of the experimental period. Dry soils (Fig. 4b & d), however, show that greater redistribution of water throughout the column occurs over the experimental time course. All profiles at the end of each experiment show levels within the main rooting zone (surface to 600 mm below) to have less water. Mean soil moisture levels for the whole soil column under each experiment are shown in Table 4. An even distribution of soil moisture was recorded only in organic dry soil at the start of the experiment. In this experimental system, water added at the start percolates down, drains to approximate field capacity and then rises as losses constantly occur at the soil surface. It is unlikely that an even distribution of soil moisture is ever achieved in the field over time, however, comparable total% water loss from start values (% water volume) varies with experimental temperature rather than soil type, with intermediate temperatures (33 °C and 27 °C) showing the highest losses of 21% (Table 3). All experiments measure a substantial mean percentage loss (>10%) over the short duration of each run. It is noted that the results have to be viewed against the fact that this is a semi-closed experimental system with respect to addition of water (no water was added during each experiment) as well as having no lateral movement of water into or out of the soil column from surrounding soil as would occur naturally. Again, it was not meant to replicate natural conditions, but rather to measure potential loss of water under the conditions set.

4. Conclusions

In summary, a first-order pilot study incorporating a series of preliminary experiments generated $T_{profiles}$ which provide evidence that soils substantially buffer thermal input over distance from a subsurface heat source at 850 mm depth with no effect above ~450 mm from the heat source detected. An additional surface heat source increases temperatures at the surface and to a depth of 300 mm below, however there is no interaction between heat sources. Modelled profiles using empirically generated data show that overall there is less effect of temperature changes within the majority of the plant rooting zone, as surface temperatures are a natural effect to which plants are adapted. However, modelled results do not fully replicate experimentally generated temperature profiles. Soil moisture profiles show differences between initially dry or wet soils, but substantial losses occur in all soils over the time course of each experiment. Whilst it is recognised that more sophisticated soil temperature models are available, T_{pbc} is not currently an input or output when a heat source is applied at a specified depth. As the first empirically produced data of its kind, the results reported will test model capabilities and provide information to facilitate future impact studies. As we report only data here it is recognised that for a full appraisal of effects on and by soil physical properties as well as biological components (crops, microbial and fungal) under natural conditions (fully open system) and varying soil types, outdoor field trials with a subsurface heat source of specific depth (~1 m) over varying seasonal conditions are needed to consider this topic in more detail.

Author contributions

JAL conceived and designed the investigation. JAL and IJ undertook the research, JAL analysed and interpreted results. JAL and DDC discussed and commented on the manuscript written by JAL and DDC. All authors reviewed the manuscript and declare no competing financial interests.

Acknowledgements

We acknowledge the support of the EPSRC Impact Accelerator Account to the University of Sheffield and National Grid Carbon Limited, UK for funding and input and Rothmet (Res eRA (RRes-Roth) for climate/soil temperature data to test the efficacy of the K-A model. We thank Mark Lomas for comments on the modelling conducted. DDC is supported by a Royal Society University Research Fellowship.

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