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Measuring and modelling the impact of outdoor pigs on soil carbon and nutrient dynamics under a changing climate and different management scenarios

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Abstract

A mixed agricultural system that integrates livestock and cropping is essential to organic, agroecological, and regenerative farming. The demand for improved welfare systems has made the practice of outdoor rearing of pigs very popular; it currently makes up 40% of the UK pig industry and has also been integrated into arable rotations. Besides the benefits of outdoor production systems, they also potentially pose environmental risks to farmlands, such as accumulation of nitrogen and phosphorus in the soil, soil erosion and compaction and carbon loss. Despite this, the impact of outdoor pigs and arable crop rotations on soil health has been under-researched relative to other livestock species. This study was conducted at the University of Leeds Research Farm from 2018 to 2020 using a combined experimental and modelling approach to understand the impact of outdoor pigs on soil carbon and nutrient dynamics. The physio-chemical properties of arable soil were measured prior to the introduction of the pigs and after introducing the pigs at the end of first and second years, consecutively. There was assessment of control sites (without pigs, mowing once a year) and pig pens (pigs in a rotation with arable crops). The soil was sampled at two different depths, 0–10 cm and 10–20 cm. It was observed that measured soil organic carbon (SOC) stocks in the soil depths of 0–10 cm and 10–20 cm layer were decreased by 7% and 3%, respectively, in the pig pens from 2019 to 2020, and total available nitrogen and phosphorus were significantly higher in pig pens than the control sites. Hence, at a depth between 0 and 20 cm, the average total available nitrogen was 2.51 and 2.68 mg kg^{-1} in the control sites and 21.76 and 20.45 mg kg^{-1} in the pig pens in 2019 and 2020, respectively. The average total available phosphorus at 0–20 cm was 26.54 and 37.02 mg kg^{-1} in control sites and 48.15 and 63.58 mg kg^{-1} in pig pens during 2019 and 2020, respectively. A process-based model (DayCent) was used to simulate soil carbon and nitrogen dynamics in the arable rotation with outdoor pigs and showed SOC stock losses of -0.09 ± 0.23 T C ha^{-1} $year^{-1}$

using the future climate CMIP5 RCP 8.5 scenario for 2020 to 2048. To reduce this loss, we modelled the impact of changing the management of the pig rotation and found that the loss of SOC stock could be decreased by shortening the period of pig retention in the field, growing grass in the field, and leguminous crops in the crop rotation.

KEYWORDS

arable rotation, carbon, climate change, nitrogen, outdoor pigs, phosphorus

1 | INTRODUCTION

Agriculture is essential for providing food and maintaining food security while concurrently delivering numerous other ecosystem services. Incorporating organic matter into agricultural soil enhances soil health by adding carbon and improving the soil structure, with the extra benefits of improving soil resilience and contributing to climate change mitigation (Amelung et al., 2020; Becker et al., 2022; Lal, 2013). As a result of climate change, all parts of the UK are expected to be warmer; by 2070, temperatures are expected to rise from 0.9°C to 5.4°C in the summer and 0.7°C to 4.2°C in the winter; summers are expected to be drier while winters are expected to be wetter (Met Office, 2020). In the agricultural sector, soil C sequestration is possible, especially with improved management techniques (Smith et al., 2008) such as integrating livestock into arable rotations (Börjesson et al., 2018; Zani et al., 2022). The integration of livestock systems supports sustainable intensification of food production while improving producer income, soil health, and environment (Franzluebbers, 2007). Integrating livestock into arable rotations provides numerous benefits to the soil in terms of soil structure, soil health, and fertilizes the soil with livestock manure (Alves et al., 2023; Brewer et al., 2023; Sekaran et al., 2021). The existing research on the effects of incorporating livestock into crop rotation has primarily centred on grazing by cattle and sheep. There are a lack of studies considering the integration of pigs into arable systems.

Outdoor pig production comprises 40% of the UK pig industry (AHDB, 2021); its popularity has been driven by animal welfare and consumer preference. However, production efficiency is particularly vulnerable to changing climate and extreme weather events. In addition, outdoor pig production does have associated environmental costs; by nature, pigs are rooters and wallowers, which removes vegetation, crop stubble and causes soil compaction by trampling (Worthington & Danks, 1994). Compaction increases soil bulk density and reduces hydraulic conductivity (Romero-Ruiz et al., 2023). Furthermore, there is a large potential for nutrient loss to both the atmosphere as ammonia (NH_3), and to aquatic ecosystems as nitrate (NO_3-) and phosphate (PO_4^{-3}), particularly on heavily compacted soils where there is higher run-off risk (Evans, 2004, 2005; Quintern & Sundrum, 2006; Williams et al., 2000). Moreover, Evans (2004) suggests that there is an increased risk of faeces and pathogens spreading from arable land where outdoor pigs remain, which could be exacerbated during wetter and winter seasons predicted under climate change.

Integrating livestock into crop rotations is one of the key principles of regenerative agriculture (Giller et al., 2021), which aims to improve soil health (Teague & Kreuter, 2020) via the deposition of faecal matter and urine by livestock (Franzluebbers & Stuedemann, 2008; Maughan et al., 2009; Sainju et al., 2011). In regenerative agriculture systems, livestock are incorporated only for short periods of time (Morris, 2021). The distribution of faecal matter and urine can differ depending on the species of livestock as well as the length of period the livestock remain on the land (Abaye et al., 1997; Watson et al., 2003). Greater concentrations of nitrogen (N), phosphorus (P), and organic matter decomposition have been observed in areas of intense pig activity, such as near the wallowing area and feeding trough (Horsted et al., 2012), because of feed inputs and nutrient distribution from dung and urine (Sun et al., 2022). In the UK, there are growing concerns about N and P pollution in water bodies from pig farming via surface runoff, soil erosion, and leaching (Jorgen et al., 2002; Webb et al., 2014; Williams et al., 2000, 2005). To avoid adverse environmental effects, the UK Department for Environment Food & Rural Affairs (DEFRA) recommends a maximum stocking density of 25–30 sows per hectare that remain for no longer than 18–24 months in the same field. The impact of outdoor pigs on soil properties is under-researched, particularly for soil organic carbon (SOC). There is an important need for continuous monitoring of the impacts of climate and outdoor pig management on soil physio-chemical properties. Process-based models, such as DayCent, have been developed to predict overall soil C and N dynamics from local to global scales (Abdalla et al., 2010; Del Grosso et al., 2008).

The DayCent model is a daily time-step version of the CENTURY biogeochemical model and is used to study C and N dynamics among plants, soil, and the atmosphere (Del Grosso et al., 2005; Parton et al., 1998).

This study was aimed at determining the impact of outdoor pigs as part of an arable rotation on soil properties, including C and N dynamics. This was achieved via the following objectives: (i) to quantify the change in soil physical and chemical properties before and after introducing pigs into an arable rotation, and (ii) to model the impact of climate and outdoor pig management scenarios on SOC and N using DayCent.

2 | MATERIALS AND METHODS

2.1 | Site description

The research was conducted at the University of Leeds (UoL) Research Farm, a commercial farm near Tadcaster (53° 51′ 44.45″ N, −1° 19′ 58.14″ W), UK. The chosen farm for our study has been under a continuous arable rotation since 1970; wheat was grown in about 60% of the rotation, with oilseed rape, barley, potatoes, and vining peas as break crops. The mean annual precipitation and temperature for the area is 674 mm and 9.2°C, respectively (Met Office, 2020). The soil present in the area is characterized as a well-drained, loamy, calcareous brown earth, specifically belonging to the Aberford series of Calcaric Endoleptic Cambisols (Cranfield University, 2018). It is underlain by dolomitic limestone originating from the Cadeby Formation (British Geological Survey, 2018). This soil type occurs extensively across the UK on gently sloping Permian and Jurassic limestone and is mainly used for arable farming. Soil depths were typically around 50–90 cm (Holden et al., 2019). The soil properties of the field used for this research prior to introducing pigs are presented in Table 1; given the proportion of sand, silt, and clay, the soil textural composition is loamy.

TABLE 1 The initial status of soil properties at the experimental site before introducing pigs into the field in 2018, where values are mean of 21 replicates repeat samples and numbers after ± are standard deviations (SD).

Depth	0–10 cm	10–20 cm
Bulk density ($g\,cm^{-3}$)	1.57 ± 0.12	1.62 ± 0.11
LOI (%)	5.99 ± 1.27	5.99 ± 1.24
Clay (%)	19.39 ± 6.13	19.65 ± 5.56
Silt (%)	32.6 ± 3.99	32.87 ± 5.11
Sand (%)	48.02 ± 8.08	47.49 ± 8.69
pH ($CaCl_2$)	6.66 ± 0.43	6.72 ± 0.46
Total nitrogen (%)	0.18 ± 0.03	0.18 ± 0.03
Total carbon (%)	2.23 ± 0.99	2.34 ± 1.01
Total organic carbon (%)	1.65 ± 0.22	1.63 ± 0.26
SOC stock (T C ha^{-1})	25.8 ± 3.12	26.25 ± 3.92
Olsen Phosphorus (mg kg^{-1})	48 ± 18.21	40 ± 16.19

This study focussed on the introduction of outdoor pigs to an arable field which occupies an area of 11 ha (Figure 1). The latest data for farm management at UoL are available from 1971 onwards; the site had previously been cropped annually with periods of set aside land and grass leys. In August 2018, winter wheat was harvested leaving 15 cm of ground stubble, and outdoor pigs were introduced in late September. Before introducing the pigs, the central area of the field was divided into seven pens of approximately 1.5 ha each using wooden posts and electric fencing. Each pen held 30 sows that were rotated after gestation. The area around the pens was used by vehicles daily to deliver feed to the pig pens. However, some areas of the field were unmanaged and not used by vehicles while the pigs were in the field and were used as control areas; the vegetation that grew on these areas was topped annually and the residues left on the field.

Enrichment is the process of changing the pigs' environment to encourage them to demonstrate more natural pig behaviours. For the pig enrichment process, 900 kg of wheat straw was spread weekly per pen for the pigs' bedding and eating purposes near to the pigs' arc. The total input of pig faeces was calculated to be 2409 kg dry matter (DM) $ha^{-1}\,year^{-1}$ and contained 39.4% C which results in the deposition of 950 kg C $ha^{-1}\,year^{-1}$. The total deposition of N from pig faeces and urine was estimated to be 269 kg N $ha^{-1}\,year^{-1}$ (Le Goff & Noblet, 2001). After the 2 years of pigs on the arable land, the usual practice of N fertilizer application at the farm was 180 kg N ha^{-1} (winter wheat), 200 kg N ha^{-1} (spring barley), 140 kg N ha^{-1} (rapeseed), and 205 kg N ha^{-1} (potato) and were used for input into DayCent. Wheat and barley were harvested leaving 15 cm of ground stubble.

2.2 | Soil sampling and preparation

Soil sampling was conducted in September 2018, prior to introducing the pigs to the field; in September 2019, 1 year after introducing the pigs; and in September 2020, 2 years after introducing the pigs. Soil was sampled from seven pig pens and four control areas (Figure 1). Three samples were taken from within each pig pen (Figure 1) using a soil core ring of 5 cm diameter and 6 cm in length, at two different depths (0–10 cm and 10–20 cm) that were analysed for bulk density (BD). In addition, a soil sample was also collected at each location at 0–10 cm and 10–20 cm depth using a screw auger and each sample was analysed

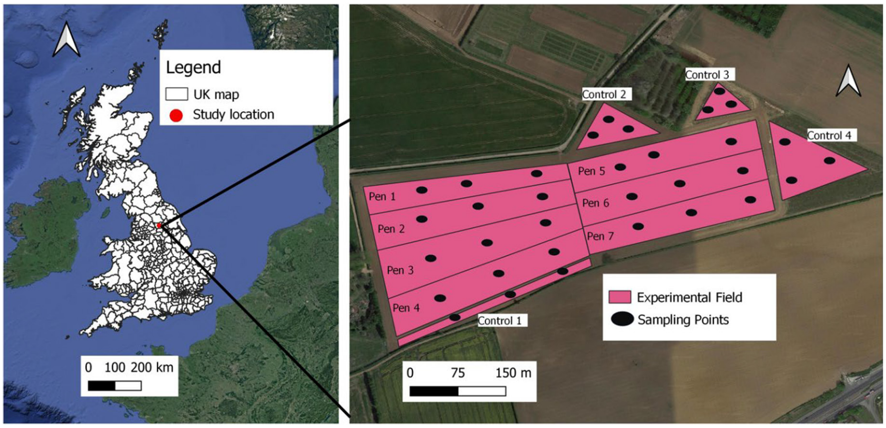

FIGURE 1 Location of study area and soil sampling points.

for moisture content, SOC, pH, Olsen phosphorus, and plant-available N. Only soil samples collected in 2019 and 2020 were analysed for plant-available N.

2.3 | Soil analysis

Bulk density was calculated as the ratio of the weight of the oven-dried soil core to the volume of the core (Poeplau et al., 2017). Moisture content was determined by measuring the weight loss after drying the fresh soil samples in an oven at 105°C for 12 h (Eze et al., 2018). Organic matter content was determined via the loss-on-ignition method where oven-dried soil samples were heated to 550°C, in which the organic matter was burnt off overnight (Ball, 1994). Plant-available N was determined via extraction of the field-moist soil in 1 M KCl solution at a ratio of 1:5 (soil: solution), the leachate was analysed for nitrate (NO_3–N) and ammonium (NH_4–N) using a SKALAR SAN++ auto-analyser (Carter & Gregorich, 2008).

The soil samples were oven-dried at 40°C for 24 h and ground to <2 mm for the determination of soil physiochemical properties. Soil pH was determined by measuring pH in a suspension of dry soil in 0.01 M $CaCl_2$ at a 1:2.5 ratio (Rowell, 1994). Olsen's method (Olsen, 1954) was used to extract soil phosphate. Total C and nitrogen N were measured by combustion using an Elemental microcube (EuroEA3000), after soil was further sieved to <100 μm. To determine SOC, a sub-sample was treated with 30 μL of 15% HCl and dried at 80°C for 2 h before being analysed for C using an Elemental microcube (EuroEA3000). Particle size analysis was conducted using 5% sodium hexametaphosphate (SPT) and then passed through a 0.53 mm sieve to separate the sand particles; the clay fraction was then determined by the pipette method and the silt fraction was calculated by subtraction (Van Reeuwijk, 2002). Soil organic C stock ($T\,ha^{-1}$) for each depth was calculated by multiplying SOC percentage, BD and sample depth.

2.3.1 | Soil aggregate and C fractionation

We used the size-density fractionation method proposed in Robertson et al. (2019) to determine the aggregate proportion and the total organic C (TOC) content of composite soil samples. This resulted in four soil fractions: dissolved organic matter (DOM), light particulate organic matter (light POM, <1.85 $g\,cm^{-3}$), heavy particulate organic matter (heavy POM, >53 μm), and mineral-associated organic matter (MAOM, <53 μm). For the measurement process, soil sieved to <2 mm was shaken with deionized water and centrifuged. The liquid was decanted using a 20 μm nylon mesh filter, giving DOM. In the remaining soil, 20 mL of 1.85 $g\,cm^{-3}$ SPT was added to separate light POM. The remaining soil was rinsed three times with deionized water and separated with a 53 μm sieve. The remaining sample is heavy POM, and the sample passed through (<53 μm) is MAOM. The light POM, heavy POM, and MAOM fractionations were oven-dried at 60°C for 24 h and analysed for organic C using an Elemental microcube (EuroEA3000).

2.4 | Model set-up for initialization, parameterization, and calibration

The DayCent model was parameterized with site-specific climate, crop, and soil data. The native vegetation and historical land use were simulated, along with modern land use and management as described by Del Grosso et al. (2011). For the spin-up model run, the model was run for 6000 years to initialize the equilibrium run, followed by planting temperate deciduous forest grown until 1849. In 1850, the forest was removed and ploughed for conversion to grassland. To validate the land use, the area was compared with maps available from 1849 onwards (Landmark Information Group, 2019). From 1950, the grassland was managed with 134 $kg\,N\,ha^{-1}$ fertilizer and light grazing with sheep continuously until 1970. A similar assumption was made by Fitton et al. (2014) for the whole of the UK. Cereal crops were grown in a rotation on the arable land from 1971 onwards, using information obtained from UoL Farm management records (Table S1). As more details on the farm management practices were available from 2009 to 2017, this period was used for model calibration (Table S2). For the model calibration, the following plant growth sub-model parameters available in the DayCent model were adjusted: prdx(1): scaling factor-the radiation use efficiency; ppdf(1): optimum temperature for plant growth; ppdf(2): maximum temperature for plant growth; Biomax: aboveground biomass for calculation of crop growth factor- C/E ratio (Del Grosso et al., 2011; Senapati et al., 2016). The model was calibrated based on actual crop yield data from 2009 to 2018 (Table 2).

2.5 | Climate data and future farm management scenarios

Historical weather data from 1853 onwards were obtained from the Centre for Environmental Data Analysis (CEDA) archive. Meteorological data, including daily precipitation and maximum and minimum temperature, from January 2002 to June 2019 were extracted from the automatic weather station at the UoL farm (53° 52′ 1.2″ N/1° 19′ 58.8″ W) (Met Office, 2012). Any gaps in the data were filled with information from the closest UK Met Office site at RAF Church Fenton (53° 49′ 58.8″ N/1° 12′ 0″ W).

Climate data for daily precipitation and maximum and minimum temperature at the site were obtained from the UK Climate Projections 2018 (UKCP18). Data were taken from the regional climate model projections at 12 km resolution, downscaled from an ensemble of global climate projections using the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project Phase 5 (CMIP5) Representative Concentration Pathway 8.5 (RCP 8.5) scenario for the period 1981 to 2048 (Met Office Hadley Centre, 2018). RCP 8.5 is the highest greenhouse gas emission scenario, often referred to as 'business as usual' and does not consider any future climate mitigation. The RCP 8.5 climate data were bias-corrected using quantile mapping (Shrestha, 2017). Based on the data availability from the meteorological station, 'present' weather data was taken to be the years 2002–2018. The RCP 8.5 climate data was divided into 'historical' weather years (1981–2018) and 'future' years (2019–2048) to assess changes.

Using the observed historical and RCP 8.5 climate data, the DayCent model was used to assess the impact of management practices on SOC stock and available N at the UoL Farm. We simulated farm management impacts on SOC stock and total available N for four scenarios taking into account expert knowledge from the UoL Farm manager and tenant farmers in arable rotational practices in the study area. These scenarios were as follows: Scenario A: 10-year arable rotation (vining pea, winter wheat, spring barley, rapeseed, winter wheat, potato, winter wheat, vining pea, winter wheat, winter wheat); Scenario B: business as usual (2 years of pigs + 4 years of arable); Scenario C: 12 months pigs + 12 months grass + 4 years of arable; Scenario D: 6 months of pigs + 6 months of grass + 6 months of pigs + 6 months of grass + 4 years of arable practices. In Scenarios B, C, and D, the 4-year arable rotation involved winter barley, rapeseed, winter wheat, and winter wheat. The N fertilizer application rates and pig stocking density were applied as described in Section 2.1.

TABLE 2 Crop yield observations (Obs.) used as model calibration data set and their respective simulated values (Sim.)

Crop	Year	Sim.	Obs.
		Yield ($T\,ha^{-1}$)	
Vining pea	2009	3.6	3.6
Winter wheat	2010	8.5	9.6
Spring barley	2011	6.5	8.0
Rapeseed	2012	3.1	4.3
Winter wheat	2013	7.5	8.1
Potato	2014	18.0	25.7
Winter wheat	2015	9.2	10.7
Vining pea	2016	2.1	3.7
Winter wheat	2017	10.6	10.0
Winter wheat	2018	9.1	10.7

2.6 | Statistical analysis

All data were analysed using The R Language and Environment for Statistical Computing version 4.2.1 (R Core Team, 2018) to identify significant differences between the treatments and controls. Prior to analysis, a normality test was conducted to identify any outliers and assess the normality of distribution using the Shapiro–Wilk test ($p > 0.05$) and box plots. The Student's *t*-test and Mann–Whitney *U*-test were conducted for parametric and non-parametric data, respectively. Control sites were considered as no treatments without disturbances, while pig pens were considered as treatments with pigs entering the crop field. The mean differences between the treatments and controls across the years were assessed using a *t*-test and all results are reported at 0.05 significance level. Data in the text are expressed as the mean of 21 samples for pig pens and the mean of 12 samples for the control sites ± standard error of the mean (SEM).

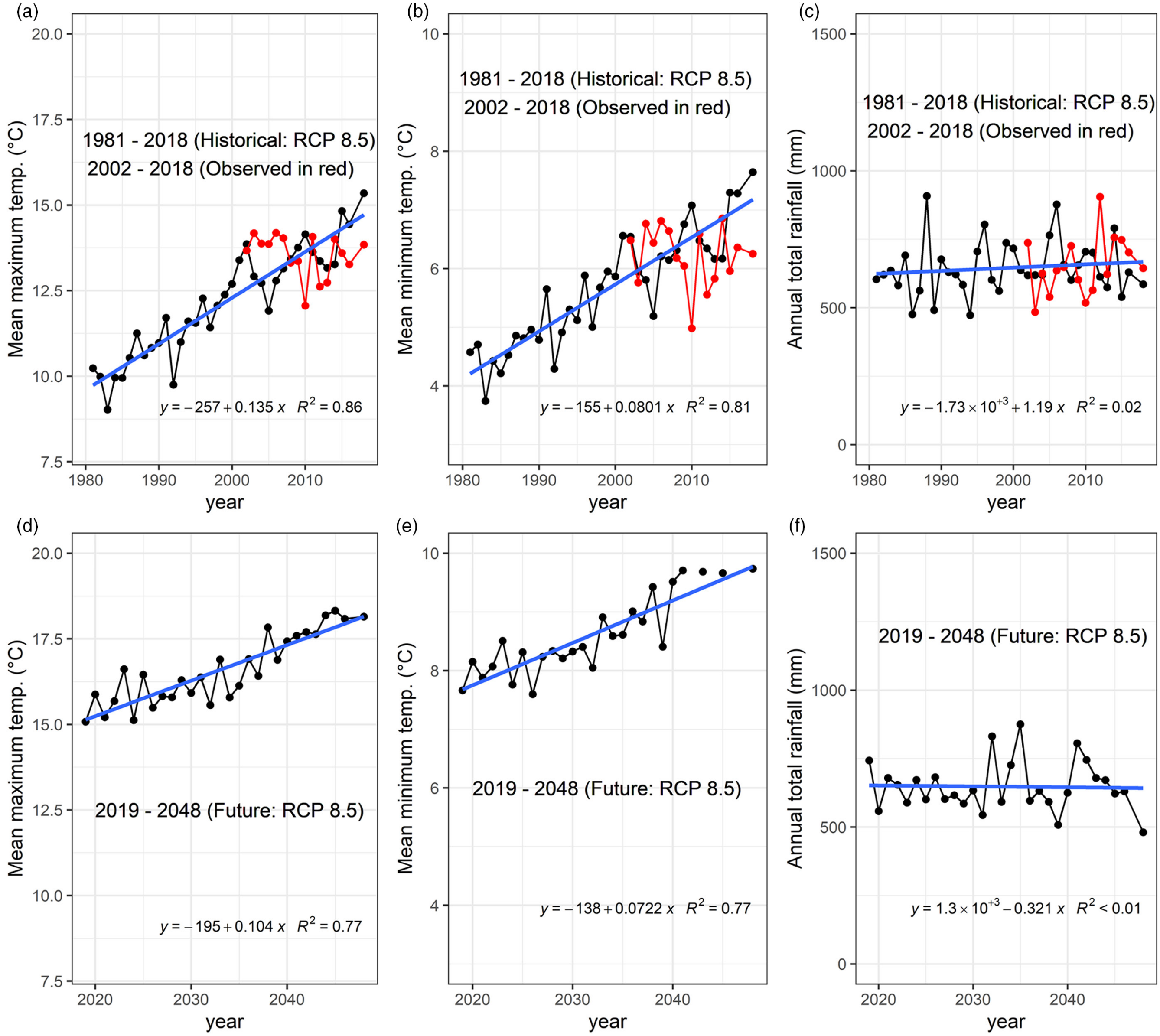

FIGURE 2 UKCP18 Climate data and trends of mean maximum and minimum temperature, and annual total rainfall for historical (1981–2018) (a–c) and future (2019–2048) (d–f) periods; and observed values from 2002 to 2018 are shown in red (a–c) (Met Office, 2020).

3 | RESULTS

3.1 | Climate scenario analysis

The observed average maximum and minimum temperatures and precipitation and historical climate projections for the CMIP5 RCP 8.5 climate data are presented in Figure 2a–c, respectively. Between 2002 and 2018, the observed period, the total annual average precipitation was 668 mm; the highest monthly total precipitation was recorded in August 2014 (149 mm) and minimum monthly total precipitation was observed in April 2011 (0.8 mm). The highest monthly average maximum temperature was recorded in July (25.3°C) whereas the minimum monthly average temperature was observed in December (−3.2°C). The average of maximum and minimum annual temperatures for the 2002–2018 period is 9.9°C.

Considering the CMIP5 RCP 8.5 climate data, precipitation fluctuates over the years with an increasing trend of 1.19 mm per year for the historical climate period (1981–2018), whereas there was a decreasing trend of 0.32 mm per year for the future climate (Figure 3f). The linear regression coefficient of temperature for both historical and future climates showed a positive trend. For the historical period, the average maximum temperature is increased every year by 0.14°C and the average minimum temperature is increased every year by 0.08°C (Figure 2a,b). Similarly, the future climate trends for the average maximum and minimum temperatures are increasing every year by 0.1°C and 0.07°C, respectively.

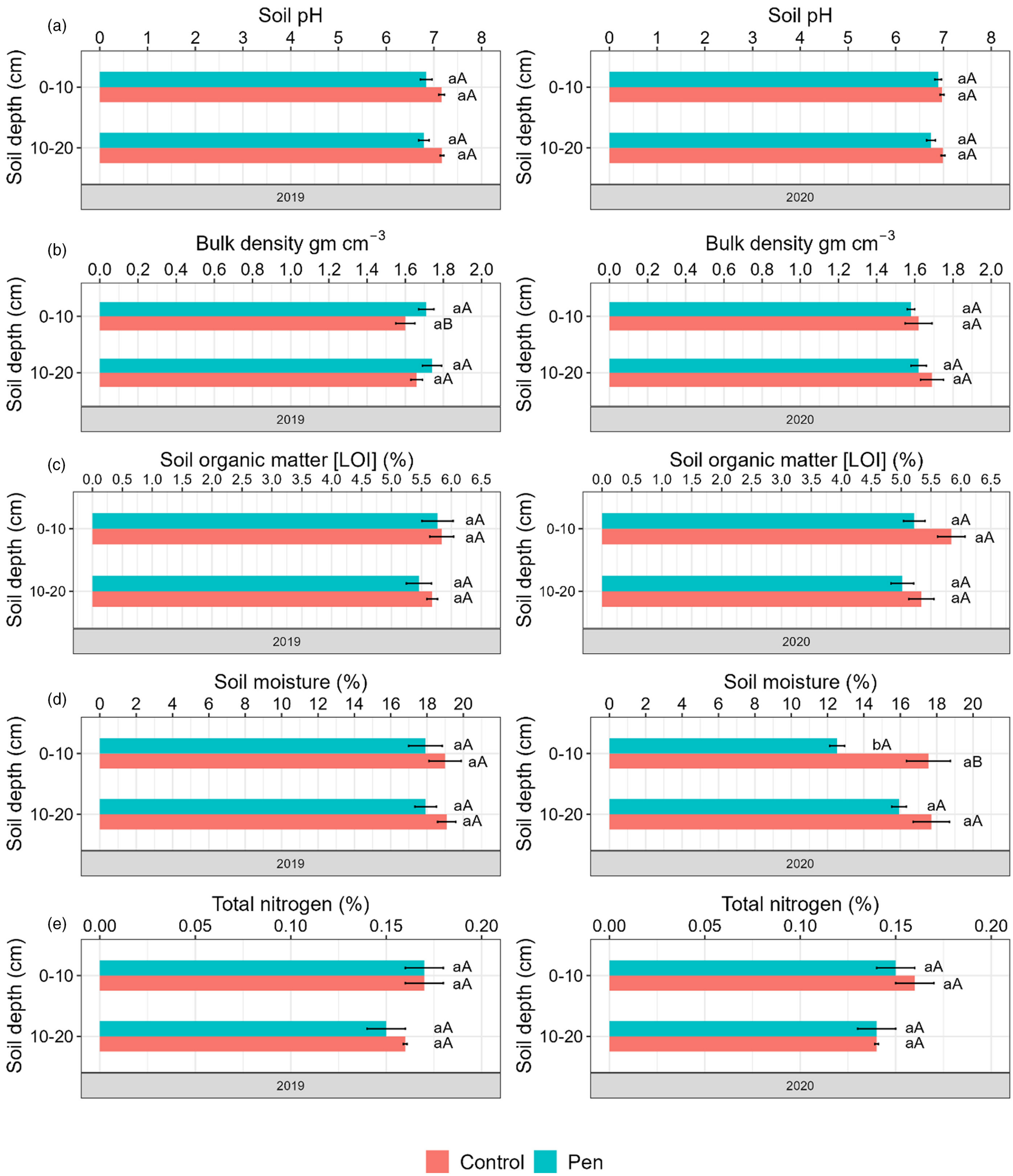

FIGURE 3 (a) Soil pH, (b) BD, (c) SOM, (d) SMC, and (e) total N measured at control sites and pig pens in 2019 and 2020. Different lowercase letters indicate significant intergroup statistical difference at $p \leq .05$; Different uppercase letters indicate significant intragroup statistical difference at $p \leq .05$.

Average annual precipitation was projected to be 651 mm, whereas the monthly total highest rainfall was observed to be 194 mm in July, with a minimum of 7 mm in May for the historical projection (1981–2018). The mean monthly maximum temperature was observed in July (25.7°C) and mean monthly minimum temperature was observed in January to February (0.1°C). The average of maximum and minimum annual temperatures for the 1981–2018 period was 8.95°C. For the future climate projection (2019–2048), average annual precipitation was projected as 645 mm, monthly total higher rainfall was observed in August (211 mm) with a lowest value in April (1.2 mm). The mean monthly maximum temperature was observed in August (28.9°C). Similarly, mean monthly lowest temperature was observed to be 0.1°C in January for the future climate model. The average of maximum and minimum annual temperatures for the 2019–2048 period is 12.75°C.

3.2 | Effect of outdoor pigs on soil physical and chemical properties

Bulk density was significantly higher in the pig pens compared with the control sites in 2019–1.71 g cm^{-3} and 1.60 g cm^{-3}, respectively (Figure 3b). Although there were no significant differences, bulk density showed a decreasing trend in pig pens over the 2-year period of outdoor pigs. There were no significant differences between soil pH, SOM, and total N between the pig pens and the control sites at either 0–10 cm or 10–20 cm (Figure 3). Without any significant differences, soil pH was higher in the control sites than the pig pens over the two-year period. After 1 year of outdoor pigs in 2019, SOM at 0–10 cm and 10–20 cm was lower in both the control sites and the pig pens compared with the 2018 baseline measurements. Although there were no significant differences statistically, SOM decreased by 10% and 9% between 2019 and 2020, respectively, in the pig pens at 0–10 cm and 10–20 cm soil depths.

There was a significant effect of the presence of outdoor pigs on soil moisture content (SMC) at 0–10 cm, showing the 29% higher in control sites than pig pens in 2020. At the 0–10 cm and 10–20 cm depths, the SMC in the pig pens was 6% lower than control sites in 2019. Soil moisture content in the pig pens increased with depth (Figure 3d). Total N decreased with depth across all years in both the control sites and the pig pens (Figure 3e). Total N decreased by 12% in the pig pens and 9% in the control sites between 2019 and 2020 at 0–10 cm without any significant difference.

3.3 | Available N and phosphorus

Plant-available N (NH_4–N + NO_3–N) and P are presented in Figure 4. Total available N was significantly higher in the pig pens than the control sites (Figure 4a) at both depths for each year, but there were no significant differences between 2019 and 2020 when looking at the pens and controls individually. The total available N for the control sites at 0–10 cm depth was 2.13 mg kg^{-1} and 2.37 mg kg^{-1} in 2019 and 2020, respectively. The total available N for the pig pens at 0–10 cm depth was 23.22 mg kg^{-1} and 23.06 mg kg^{-1} in 2019 and 2020, respectively. Similarly, the total available N for the control sites at 10–20 cm depth was 2.89 mg kg^{-1} and 3 mg kg^{-1} in 2019 and 2020, respectively. The total available N for the pig pens at 10–20 cm depth was 20.42 mg kg^{-1} and 17.84 mg kg^{-1} in 2019 and 2020, respectively. There were significant differences between the control sites and the pig pens in 2019 and 2020 for both soil depths. We did not observe any significant differences in P concentration in the control sites across the years, but significantly higher P was observed for the pig pens in 2020 compared with 2019. Phosphorous distribution in the soil was lower in the control sites than for the pig pens; a higher level of P was observed at 0–10 cm than at 10–20 cm. For the pig pens, the P level increased from 2019 to 2020 at 0–10 cm and 10–20 cm by 36% and 27%, respectively.

The simulated results from the DayCent model showed that total available N accumulated in pig pens during the summer; this declines in autumn and winter as the soil wets (Figure 5). For the control sites, there was comparatively lower available N compared with the pig pens. In 2019, after 1 year of outdoor pigs, total accumulation of available total N was 8347 mg kg^{-1}, whereas in 2020, after 2 years of outdoor pigs, was 8555 mg kg^{-1}. Total available N accumulation in control sites was 6060 mg kg^{-1} and 566 mg kg^{-1} in 2019 and 2020, respectively. The highest accumulation of available N was observed as 39 mg kg^{-1} in mid-June 2019, whereas in 2020 the highest accumulation was observed as 48 mg kg^{-1} at the end of May in the pig pens.

3.4 | Soil C and C fractionation

Figure 6 shows the total C, SOC, and SOC stock for the control sites and the pig pens in 2019 and 2020. Although the difference was not significant, total C was lower in the pig pens compared with the control sites in 2019 and 2020. In 2019, total C at 0–10 cm and 10–20 cm was 7% and 14% lower in the pig pens than the control sites. Similarly in 2020, the total C content of soil in pig pens was 11% and 10% lower than the control sites at 0–10 and 10–20 cm soil depths, respectively. The difference in total C between the control sites and the pig pens was similar to that of SOM (Figure 3c). There was no significant difference in SOC or SOC stock between the treatments or the years. The amount of SOC was higher in 0–10 cm than 10–20 cm depth in both the control sites

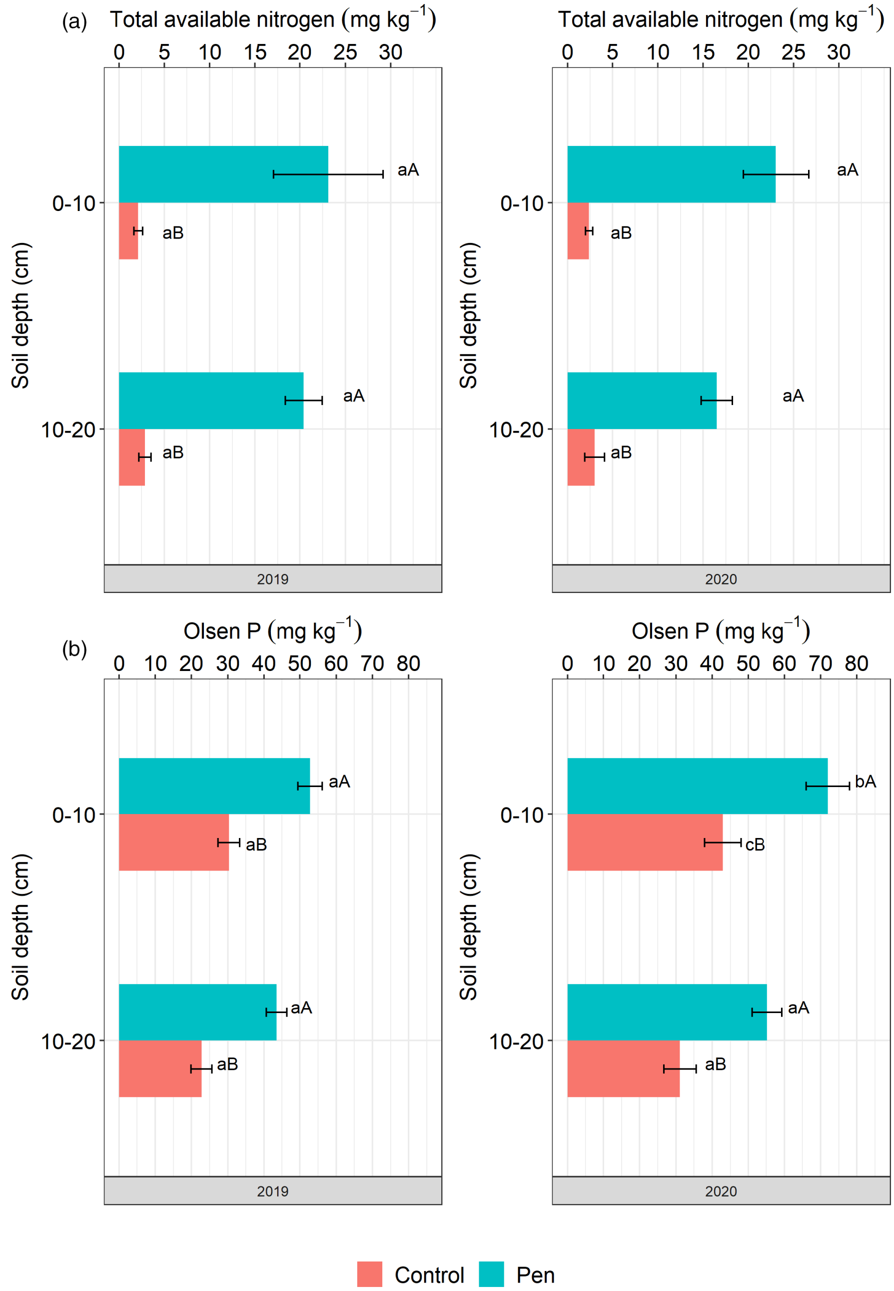

FIGURE 4 (a) Total available N and (b) Olsen phosphorus measured at control sites and pig pens in 2019 and 2020. Different lowercase letters indicate significant intergroup statistical difference at $p \leq .05$; Different uppercase letters indicate significant intragroup statistical difference at $p \leq .05$.

and the pig pens in both 2019 and 2020. Soil organic C stock was higher in the pig pens compared with the control sites at 0–10 and 10–20 cm depth in 2019. In 2020, SOC stock was reducing in the pig pens but increasing trend in control sites (Figure 6c).

Figure 7a shows the soil size and density fractionation in the control sites and the pig pens. There were significant differences among the fractionations within the treatments. Mineral-associated organic matter was higher for the control sites and heavy POM was higher for the pig pens. Light POM was similar for the control sites and the pig pens. The amount of C in light POM in the pig pens was 11% higher than the control sites at 0–10 cm soil depth, while at 10–20 cm depth was 5% higher in the pig pens than the control sites.

The lowest aggregate-associated SOC was observed in light POM and the highest was observed in MAOM (Figure 7b). There were no significant differences among the fractions for the control sites and the pig pens at either sampling depth. However, among the different fractionations at each depth, there were significant differences between light POM and the heavy POM and MAOM fractions. At 0–10 cm the proportion of C provided by light POM was 10% higher in the pig pens than the control sites. Similarly, light POM was 6.5% higher in the pig pens than the control sites at 10–20 cm. Carbon stock was

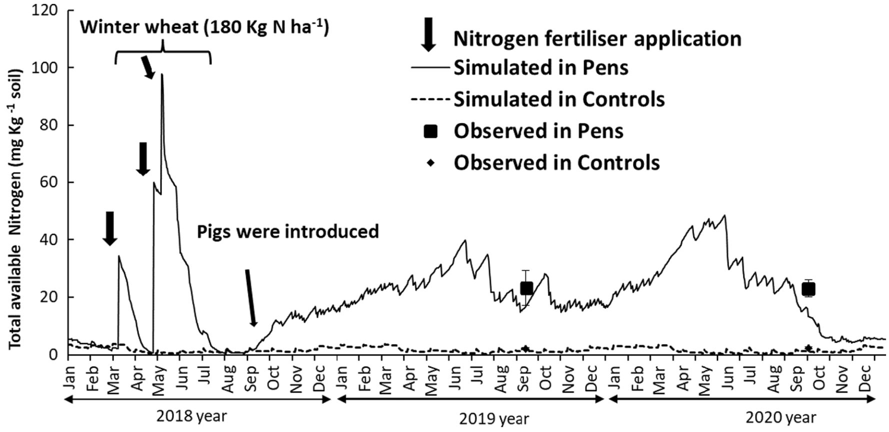

FIGURE 5 Observed and simulated total available N for pig pens and control sites.

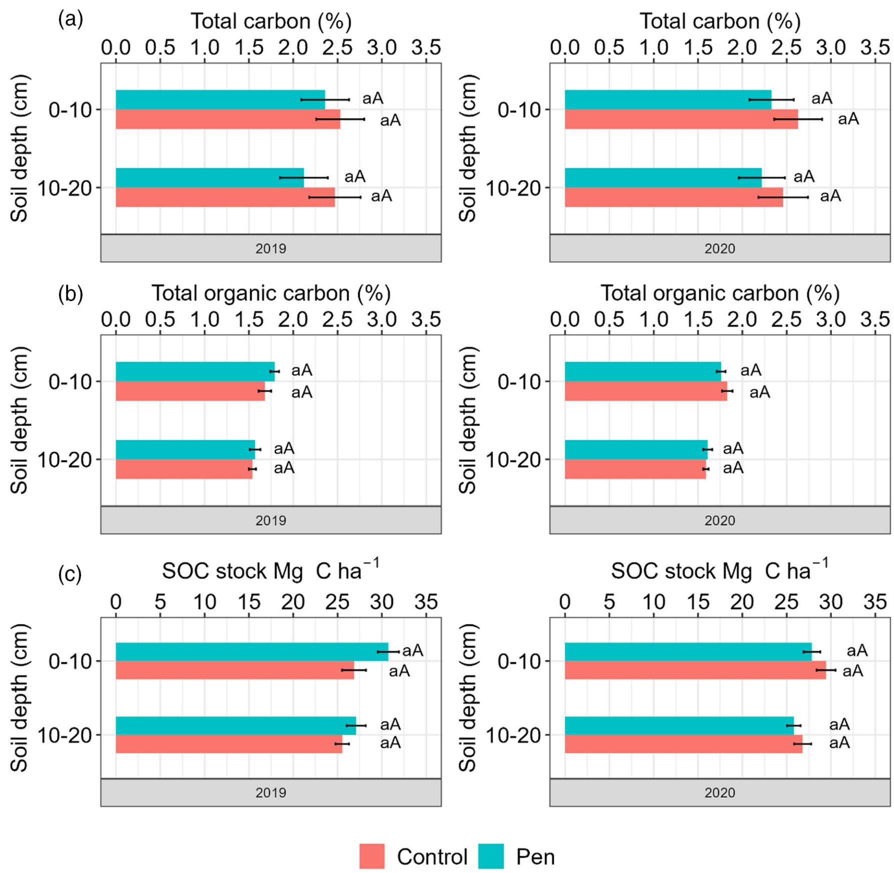

FIGURE 6 (a) Total carbon, (b) SOC (%), and (c) SOC stock measured at control sites and pig pens in 2019 and 2020. Different lowercase letters indicate significant intergroup statistical difference at $p \leq .05$; different uppercase letters indicate significant intragroup statistical difference at $p \leq .05$.

significantly higher in MAOM than the heavy POM and light POM fractions (Figure 7c) in general.

3.5 | Modelled long-term SOC stock and total available N changes with different management scenarios

The amount of time the pigs remained in the field was very influential regarding the long-term change in SOC stock as simulated by the DayCent model (Figure 8). On one hand, the DayCent model simulation suggested that shortening the length of time the pigs were kept on the field for and allowing grass cover would increase the SOC stock, while allowing the pigs to remain in the fields for one or 2 years notably decreased SOC stock. Managing the rotation of the pigs and the grass cover in the pig pens could mitigate the negative effect on SOC stock in the field. A rotation implementing 6 months of pigs and 6 months of grass for 2 years and a four-year cereal rotation increased the C stock on average over the period modelled by 0.03 ± 0.23 T C ha^{-1} year^{-1}. Similarly, the arable rotation increased the C stock by 0.01 ± 0.25 T C ha^{-1} year^{-1}. However, 2 years of pigs with 4 years of arable rotation, and 1 year of pigs and

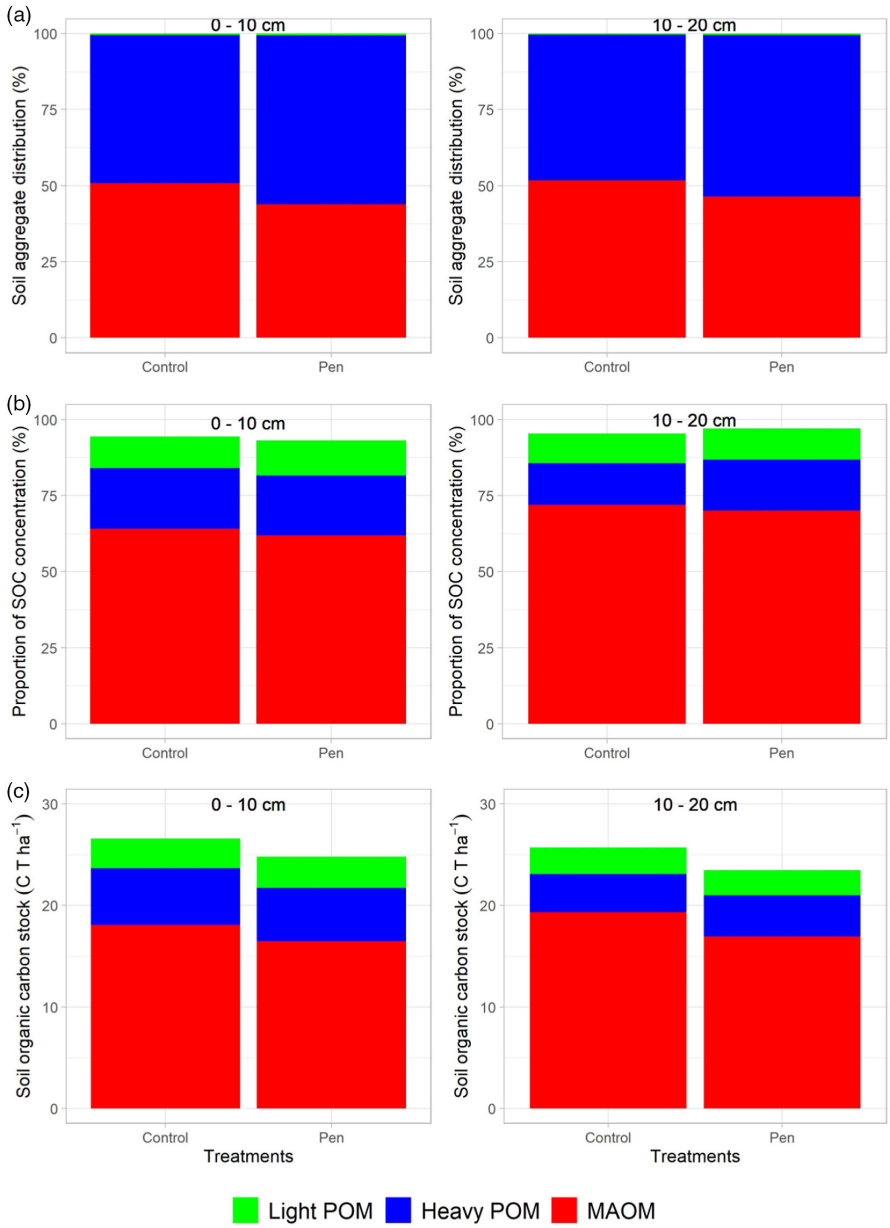

FIGURE 7 (a) Soil aggregate distribution, (b) proportion of SOC concentration, and (c) SOC stock in soil aggregate distribution by density fractionation in soils measured at control sites and pig pens in 2020.

1 year of grass with 4 years of cereal crops decreased the SOC stock by 0.09 ± 0.23 T C ha^{-1} year^{-1} and 0.10 ± 0.23 T C ha^{-1} year^{-1}, respectively.

Table 3 presents the annual totals of simulated net primary production (NPP), heterotrophic respiration (R_h), and net ecosystem exchange (NEE) for various farm management scenarios. Similar NPP was simulated for the winter wheat, barley, and rapeseed. The highest NPP (613 g C m^{-2} year^{-1}) was simulated at 6 months of pig and 6 months of grass, followed by grass only and pigs only, by 358, and 60 g C m^{-2} year^{-1}, respectively. Similarly, the highest R_h was from 6 months of pig and 6 months of grass 360 g C m^{-2} year^{-1}, followed by pigs only, and grass only by 208, and 177 g C m^{-2} year^{-1}, respectively. The highest C sink was simulated at 6 months of pigs and 6 months of grass at 253 g C m^{-2} year^{-1}, followed by grass only, 181 g C m^{-2} year^{-1}, respectively. During the pigs only remaining in the field, the simulation showed the soil as a C source of 119 g C m^{-2} year^{-1} and 166 g C m^{-2} year^{-1} in scenarios B and C, respectively (Table 2).

The annual total available N was also predicted by the DayCent model over a 40-year period for the four management scenarios as shown in Figure 9. Lowest available N was observed in the arable rotation and highest in the 2 years with pigs and 4 years with arable (Figure 9a,b), the latter being the 'business as usual' scenario. The 2 years of pigs with 4 years of cereals show a clear peak of available N when pigs remain in the field, followed by the 2 years of grass with pigs and 4 years of cereals. In contrast, the shorter time the pigs remained and grass growing showed lower available N (Figure 9c,d). The magnitude of the peak of total available N was dependent on the duration of pigs remaining in the

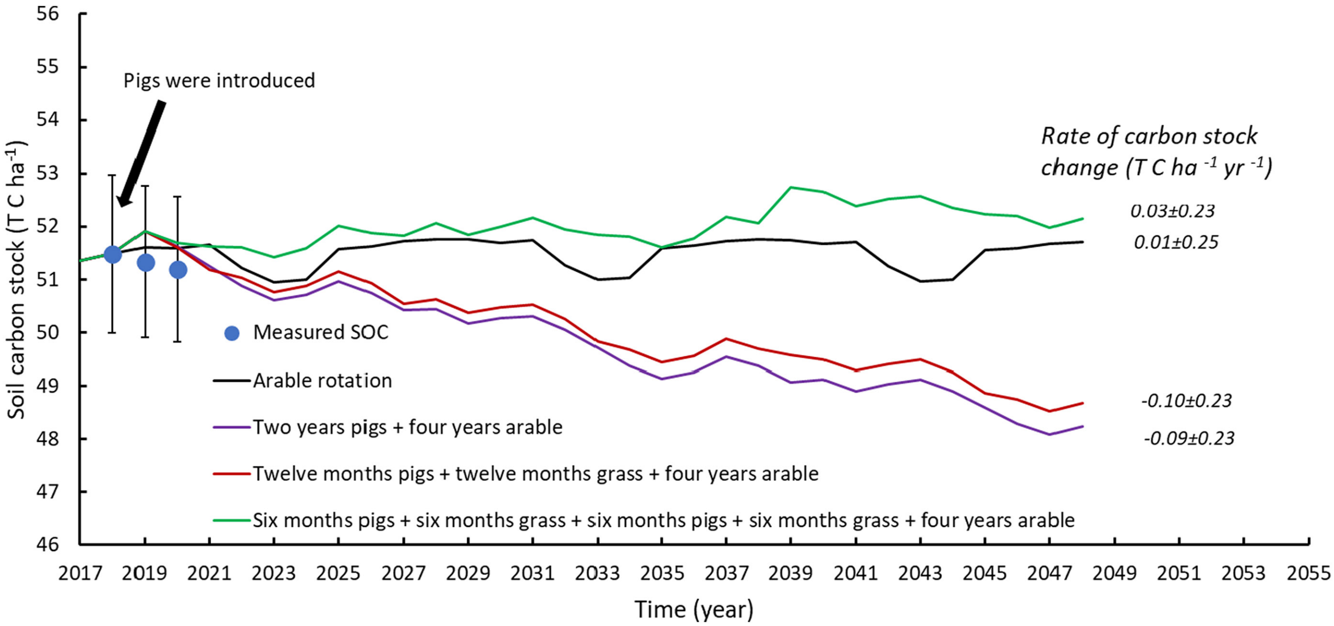

FIGURE 8 Simulated soil carbon stocks in the top 20 cm for six management scenarios at the UOL Farm using the RCP 8.5 scenario.

TABLE 3 The modelled average annual C totals of NPP, R_h, and NEE for the various farm management scenarios (g C m^{-2} $year^{-1}$).

Variable	Farm management scenarios	Winter wheat	Winter barley	Rapeseed	Pigs only	Grass only	Six months of pigs and six months of grass
	A	1160	_	1176	_	_	_
	B	1105	1104	1187	60	_	_
NPP	C	1100	1076	1181	43	358	_
	D	1122	1185	1204	_	_	613
	A	271	_	229	_	_	_
	B	235	198	220	180	_	_
Rh	C	239	231	233	208	177	_
	D	273	369	296	_	_	360
	A	889	_	947	_	_	_
	B	870	906	967	−119	_	_
NEE	C	861	845	948	−166	181	_
	D	848	816	907	_	_	253

Note: A: Arable rotation, B: 2 years of pigs + 4 years of arable rotation, C: 12 months pigs + 12 months grass + 4 years of arable rotation, D: 6 months of pigs + 6 months of grass + 6 months of pigs + 6 months of grass + 4 years of arable rotation. A negative (−) sign in the number indicates carbon as a source.

field. During cereal growing years, there was less available N compared with the period when pigs were in the field.

4 | DISCUSSION

4.1 | Impact of outdoor pigs on soil compaction

Our findings showed that the introduction of pigs did not increase soil BD. Bulk density was already high in the arable field, and so the soil compaction at the top 0–10 cm decreased following the introduction of pigs to the field (Figure 3b) because of trampling which deformed the soil structure (Warren et al., 1986). Studies have shown that livestock can directly affect soil compaction (Agostini et al., 2012; Rasby et al., 2014); however, our findings showed that soil compaction was not enhanced after introducing pigs into the field given the high initial BD. Different from our result, Bell (2010) found that soil compaction after cattle were introduced into an arable field, and thus soil infiltration and porosity decreased. There are no studies on how outdoor pigs specifically influence soil compaction; however, the body weight of animals contributes to their level of soil

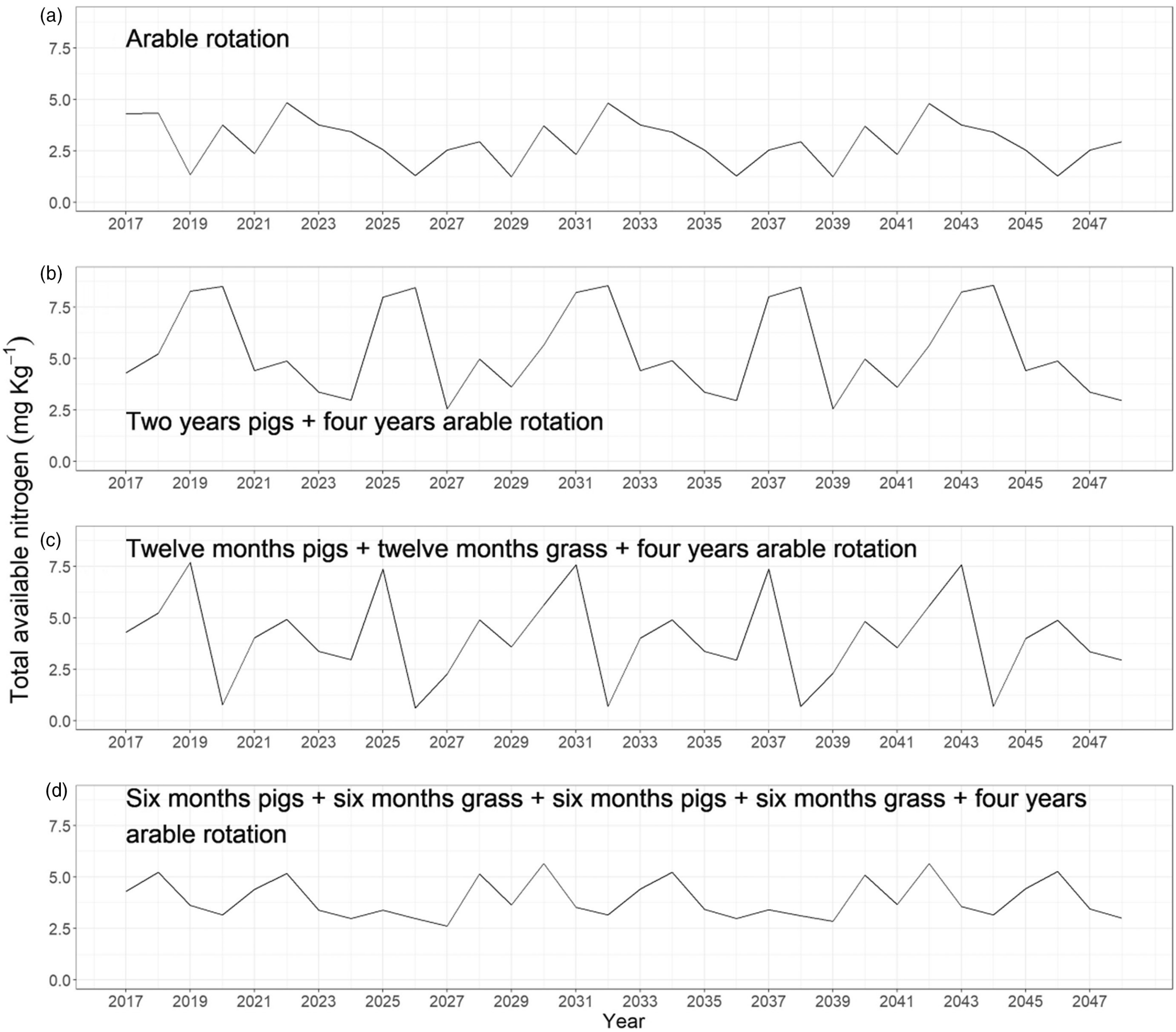

FIGURE 9 Simulated total available N between 0 and 20 cm for the four management scenarios at the UOL Farm and using RCP 8.5 scenario (2018–2048).

compaction, as reported by Serrano et al. (2023), who stated that bovine cows exhibited higher soil compaction (up to 190 kPa) than sheep (80 kPa) because of their body weights. The study by Holden et al. (2019) reported that soil compaction is higher in arable field of UOL, which is in line with our current study that indicates very high BD observed in arable field.

Aggregate distribution is important in terms of maintaining the structure of the soil (Zheng et al., 2018); a good soil structure can readily infiltrate water. Our results did not indicate any significant differences in soil size-density fractionation between the control sites and the pig pens. The soil aggregate size distributions (Figure 7a) reveal that the large fraction (heavy POM) was greater in the pig pens than the control sites at both depths. Light POM was 10% and 6.5% higher in pig pens than control sites at 0–10 and 10–20 cm, respectively, indicating that the fresh C inputs from stubble residues and spread straw are allocated to the soil's light POM fraction. Although soil's light POM fraction was increased resulting from short-term experiment conducted, however, soil BD revealed enhanced soil compaction. Conversely, Sarker et al. (2022) reported that an increase in the soil light POM revealed an impact on soil compaction causing an enhancement in the soil porosity.

4.2 | Impact of outdoor pigs on SOC stock, total available N changes, and soil C fractionations

In the present study, SOC stock did not significantly change after pigs were introduced (Figure 6b), and there was no significant difference in SOC (%) between the treatments. The higher SOC (%) was observed in control sites compared with the pig pens, as the soil remained undisturbed, however in the pig pens, the soil was disturbed by pigs and so had limited vegetation growth in the pig pens compared with control sites. The lower SOC value in the pig pens compared with the control sites is indicative that faeces deposition did not contribute to the formation of SOC; this was also observed by Hatfield et al. (2007). Waters et al. (2017) suggested that the effects of grazing intensity management on SOC are affected by the amount of ground cover and the amount of organic matter. There was limited vegetation growth in the pig pens during the present study and SOC stock could be improved by incorporating temporary grass-clover leys and organic amendments. The low SOC stock in the arable field could be improved by crop rotation with temporary grass-clover leys and organic amendments (Zani et al., 2023).

DayCent simulations indicated average SOC losses of 0.09 ± 0.23 T C ha^{-1} $year^{-1}$ when the current rotation of 2 years of pigs with 4 years of arable was extended into the future under the RCP 8.5 scenario. Pigs' hooves disturbed the soil at the 0–10 cm depth, which was observed during a field visit. As the field is without grass cover, and organic matter input is only from pig faeces and straw, the effect of tillage on bare soil is associated with potential losses of SOC (Table 3). The management practice of 6 months of pigs + 6 months of grass + 6 months of pigs + 6 months of grass + 4 years of arable gave rise to SOC gains of 0.03 ± 0.23 T C ha^{-1} $year^{-1}$, as the grass covered in the field and pig faeces and urine contributed to storing C in the soil (Table 3). This indicates that shortening the period of pig retention and grass cover could be potentially beneficial for C sequestration in the future. The highest available N was observed in the 2 years of pigs with 4 years of arable scenario (Figure 9b) which could lead to high N loss through emissions, surface runoff and leaching. However, 2 years of pigs with grass cover was observed to reduce the excess available N that could be lost as NH_3 and nitrous oxide.

As there were no significant changes to SOC between the pig pens and control sites, the density fractionations were analysed to understand the SOC proportion in light POM, heavy POM, and MAOM; this helped to identify which fractions were more sensitive to soil management (Oades, 1984; Von Lützow et al., 2006). The SOC (%) in the MAOM fraction ranged from 62% to 70% in the pig pens at 0–10 cm and 10–20 cm soil depths. The SOC in the light POM fraction was higher by 5% and 10% in the pig pens than control sites at 0–10 cm and 10–20 cm soil depth, respectively (Figure 7b). The higher proportion of light POM in pig pens compared with the control sites can be attributed to the input of light-density litters, stubble residues and spread straw which did not occur in the control treatment.

4.3 | Potential for nitrogen and phosphorus losses to aquatic water bodies from outdoor pigs

The introduction of outdoor pigs resulted in significantly higher concentrations of soil inorganic N and P compared with the control sites without outdoor pigs (Figure 4), which could be attributed to the fresh N and P inputs from concentrated feed and straw bedding which were then redistributed as dung and urine. The higher concentration of N and P in food results in the higher percentage of N and P content in faeces and urine (Jørgensen et al., 2013). Our finding corroborates those of a study conducted on organic pig production in the southwest of England (Sun et al., 2022), where higher inorganic N and available P were found in organic pig fields compared with fields without pigs.

The accumulated inorganic N is lost to the environment via NH_3 volatilization, nitrous oxide emission and leaching of NO_3- to groundwater (Medici et al., 2021). The pig pens had substantially higher levels of P and N compared with the control sites. Williams et al. (2000) reported that NO_3- leaching was lower in grass-covered arable land, whereas there was substantial NO_3- leaching from bare soil. In our study, the pigs' faeces, urine, and straw spread for bedding added P and N to the soil that could be lost to the environment via emission, runoff, and leaching. The simulated results also reveal that N increased in the summer and decreased in the autumn and winter as the moisture level rises (Figure 5), indicating a risk of N leaching and loss to the environment. Proper management of moving the pig arc, feeding trough and wallowing area, stocking density, grass covering, and timely rotation could therefore prevent the risk of NO_3- leaching from the soil environment when available N is high and topsoil layer is deformed.

5 | CONCLUSION

Arable land management with livestock rotation is important for both soil quality and animal welfare. The inclusion of pigs in an arable livestock rotation has been studied far less than the inclusion of other livestock such as cattle and sheep. Our findings show that soil nutrients, especially P and plant-available N, increased following the introduction of pigs into arable rotations and that these nutrients can be subsequently lost to the environment when the soil is left bare for extended periods of time. We observed no effect on soil pH, BD, SOC as a result of the introduction of pigs into arable rotations during our study period. Process-based modelling indicated that current practices such as 2 years of outdoor pigs and 4 years of arable rotation could reduce soil C stocks in the long term under a range of climate change scenarios. The reduction in soil C stock can potentially be mitigated with sustainable management practices, such as shortening the period in which pigs are on the field, reducing the occupancy rates, and introducing grass leys into the rotation.

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With this paper, we as a team honour the scholarly leadership of critical zone researcher Professor Steven Banwart, whose recent and sudden passing we grieve. Steve was an expert in soil and water resource protection for food security. Steve's legacy within our research community will be to continue global leadership in tackling global challenges.

CONFLICT OF INTEREST STATEMENT

The authors of this study declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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