A framework for integrating the terrestrial carbon stock of estates in institutional carbon management plans

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Abstract

Many institutions have substantial landholdings, but few consider soil carbon preservation and augmentation in their carbon management plans. A methodical framework was developed to analyse terrestrial carbon stocks (soil and tree biomass) for credible carbon offsetting strategies in institutional land. This approach was demonstrated at two farms (805 hectares) managed by Newcastle University. Soil carbon for three depths (0–30 cm, 30–60 cm and 60–90 cm) and above-ground tree biomass were quantified. These data provided a terrestrial carbon baseline to evaluate future land management options and effects. Historical land-use records enabled the following comparisons: (1) agricultural land vs. woodland; (2) arable land vs. permanent grassland; (3) organic vs. conventional farming; (4) coniferous vs. broadleaved woodland; and (5) recent vs. long-established woodland. Carbon storage (kg/m²) varied with land usage and woodland type and age, but only agricultural land vs. woodland, and for agriculture, arable land vs. permanent grassland, significantly affected the 0–90 cm soil carbon. At the university-managed farms, current terrestrial carbon stocks were 103,620 tonnes in total (98,050 tonnes from the 0–90 cm soil and 5,569 tonnes from tree biomass). These terrestrial carbon stocks were equivalent to sixteen years of the current carbon emissions of Newcastle University (6,406 tonnes CO₂ equivalents-C per year). Using strategies for alternative land management, Newcastle University could over 40 years offset up to 3,221 tonnes of carbon per year, or 50% of its carbon emissions at the current rate. The methodological framework developed in this study will enable institutions having large landholdings to rationally consider their estates in future soil carbon management schemes.

KEYWORDS
carbon augmentation, land management, soil carbon, terrestrial carbon storage, tree carbon
1 INTRODUCTION

The Paris Agreement has built consensus amongst 197 state parties to limit the increase in global average temperature to 1.5°C above pre-industrial levels (UNFCCC, 2016). Soil carbon management has a vital role to play in achieving this goal, exemplified by the ‘4 per 1000’ initiative (Lord & Sakrabani, 2019; Minasny et al., 2017). Government aims to mitigate climate change would be unachievable if contributions from individual organizations were absent (Knuth et al., 2007). Many institutions, including universities, also recognize the need to address the climate emergency (Knuth et al., 2007; Lewis & Patton, 2010; Mazhar et al., 2014; Robinson et al., 2018). When the Climate Neutral Network (CN Network, 2009) was launched by the United Nations Environment Programme in 2008, six universities from the USA, UK, Spain and China committed to building low-carbon campuses (Shin, 2009). By December 2013, 669 academic institutions became signatories of The American College and University Presidents’ Climate Commitment (ACUPPC) which aims to reduce 80% of greenhouse gas (GHG) emissions by the middle of 21st century (Delaney, 2010; Peterson, 2013). This is important, because approximately 2% of the GHG in the USA are produced from colleges and universities (Shin, 2009; Sinha et al., 2010). In 2018/19, a total of 161 universities in the UK emitted nearly 11 million metric tonnes of CO₂, constituting 3% of UK emissions (Mitchell-Larson et al., 2021). In the UK, many English universities have launched ambitious carbon management plans, as required by the Higher Education Funding Council for England, with similar plans in Scottish and Welsh universities (Lewis & Patton, 2010). These commitments show how academic institutions globally can voluntarily contribute to national and multi-national climate change mitigation plans and set an example for other institutions. While the important role of universities in national carbon emission reduction plans has been acknowledged widely (Mazhar et al., 2014; Mitchell-Larson et al., 2021; Robinson et al., 2018), some universities may not achieve their ambitious carbon reduction goals (Warner, 2016).

As more institutions adopt ambitious net-zero or neutral targets for their future carbon emission, plausible carbon offsetting strategies become increasingly important. In their latest briefing at the 26th United Nations Climate Change Conference (Mitchell-Larson et al., 2021), climate change experts have emphasized that higher education institutions should carry out nature-based carbon removal such as growing trees and restoring forests at scale. However, a review of sixteen university carbon management schemes available online showed that none considered terrestrial carbon, including carbon stored in soils and by plants, in a quantitative way (Table S1 and related discussion in Supporting Information). Nevertheless, many academic institutions have substantial landholdings. For example, Newcastle University occupies an urban campus of around 20.2 hectares in north-eastern England. But more significant in terms of its institutional land management are two research farms, Cockle Park Farm and Nafferton Farm, with a total land area of 805 hectares. As Newcastle University is working towards net-zero carbon dioxide emissions by 2030 (Boot, 2020), it seems pertinent to consider management opportunities for the entire estate to capture and store atmospheric CO₂, setting an example for institutions globally with significant landholdings. For example, Oxford and Cambridge Universities are amongst the largest landowners (23,151 and 18,433 ha, respectively) in the UK (Barbiroglio, 2018). The ten largest college campuses in USA cover above 45,982 hectares (Egan, 2019). Many other government and non-government organizations and private sector institutions also own significant amounts of land. For instance, amongst the private water companies in England, United Utilities has the largest landholding of around 57,061 hectares (Shrubsole, 2016). Local authorities own approximately 4% of land in England (Shrubsole, 2020). In Scotland, approximately 32,780 hectares of land are owned by 32 councils (Picken & Nicolson, 2019). Local authorities in Wales own land used for farming purposes with just over 16,441 hectares (Welsh Ministers, 2018). There are 125,857 hectares of golf course in Great Britain, which is similar to the whole public park area (125,048 hectares), and the majority of these golf courses are owned by local authorities (Shrubsole, 2020). A recent questionnaire survey of 27 local authorities from across the UK revealed that 81% of the councils had declared a climate change emergency and 70% had committed to additional tree planting, but only one council had related its tree planting target to carbon emissions across the authority (Ross, 2020).

Optimized land management has a significant potential for greater carbon sequestration (Kaplan et al., 2012; Rees et al., 2018; Wang et al., 2019; Wiesmeier et al., 2019). The ‘4 per 1000’ initiative, for example, seeks to increase soil organic carbon globally by the annual rate of 0.4% to compensate the GHG emissions resulting from human activities (Lord & Sakrabani, 2019; Minasny et al., 2017). However, achieving the ‘4 per 1000’ goal is a formidable challenge in temperate regions, as has been exemplified with agricultural field experiments in the south-eastern UK (Poulton et al., 2018), and this applies even more so in the northern UK, where soil C content is already higher than in the south (Bradley et al., 2005; Feeney et al., 2021). Nonetheless, the soil organic carbon pool has experienced substantial losses under agricultural management, but could reach an equilibrium in other ecosystems such as forests or prairies (Jarecki & Lal, 2003). Approximately
The aim of this research was to develop and demonstrate a methodological framework for quantifying and managing terrestrial carbon on institutional estates. The objectives of the framework are as follows: (1) to establish the current carbon stocks of estates as a database and future reference point, (2) to obtain from the integration of these data with land-use records a quantitative understanding of how management affects terrestrial carbon stocks and (3) to derive from this analysis realistic and locally appropriate strategies for achieving institutional carbon reduction goals by changes in land management.

2 | METHODOLOGY

2.1 | Methodological framework

The methodological framework of this study is illustrated in Figure 1. First, the current soil and tree carbon stock on the institutional estate was surveyed to establish a baseline for future reference and a dataset for the analysis of land-use effects. Next, these field data were integrated with the institutional and publicly available land-use records to derive quantitative understanding of land management effects on terrestrial carbon in the institutional estate. Finally, the future terrestrial carbon stores were predicted as a function of future land management scenarios and quantitatively related to the institutional carbon emissions and reduction targets. The annual carbon emissions (CO₂ equivalents-C) for Newcastle University in the academic year 2019/20 were obtained from its carbon management plan (Boot, 2020).

2.2 | Study sites

The methodological framework was demonstrated in northeast England, at Cockle Park Farm (307 hectares; 55°12’55.4"N, 1°41’04.6"W) situated 29 km north of Newcastle upon Tyne on land owned by Newcastle University, and at Nafferton Farm (498 hectares; 54°59’07.1"N, 1°53’59.4"W) located 19 km west of Newcastle, where the University has a 999-year lease on the land. North-east England receives an average annual rainfall of 902 mm (MetOffice), and the recorded average temperature varies from 5°C in winter to 13°C in summer. Soils at Cockle Park Farm (predominantly Luvic Stagnosols of the Dunkeswick and Hallsworth Series) (Hopkins et al., 2011; Jarvis et al., 1977) and Nafferton Farm (predominantly Dystric Stagnosol of the Brickfield series) (Jarvis et al., 1977; Zani et al., 2020) are developed on Pleistocene superficial deposits (glacial till, alluvial sand) that overlie Upper Carboniferous rocks (sandstone, mudstone, coal) and have been texturally classified as loamy soils (silty loam, heavy clay loam, medium clay loam and sandy loam) in all but one small area at Cockle Park Farm classified as clay (FAO, 2015; Farewell et al., 2011).

2.3 | Soil and tree carbon survey

The soil collection work was conducted in April 2018 (agricultural land, Cockle Park Farm), March 2019 (agricultural land, Nafferton Farm), October 2019 (woodlands, Cockle Park Farm) and February 2020 (woodlands, Nafferton Farm). The sampling locations were evenly distributed over the agricultural land and woodlands, and each crop area and every soil type were covered. Overall, 102 points were sampled across 2 farms: 55 points were sampled at Cockle Park Farm (39 plots in agricultural land vs. 16 plots in woodlands), which resulted in 163 soil samples (approx. 350 g each sample). At some locations, soils from 60 to 90 cm could not be obtained due to obstacles encountered when coring. Similarly, there were 139 soil samples from three soil depths at 47 sampling points at Nafferton Farm (31 plots in agricultural land vs. 16 plots in woodlands). Soil was sampled at three depth increments (0–30 cm, 30–60 cm and 60–90 cm) with tractor mounted coring equipment in agricultural land and using a hand auger in woodlands. The coring equipment or hand auger was drilled to a depth of up to 1 m, and after coring, the tube with the soil core was placed horizontally on the ground. A tape measure was used to divide the soil cores into 30-cm intervals where the first segment (0–30 cm depth) started from the top of the tube. Each sample was then placed and sealed in an individual zip-top plastic bag. After sampling, the soils were moved back to the laboratory and stored at 4°C in a cold room. Large stones, roots and other plant debris were removed before oven-drying the soils for about 48 h at 105°C to a constant weight, while recording the loss of weight as the water content of the soils. Afterwards, samples were passed through a 4.75-mm sieve because soil macroaggregates below this size drive the long-term carbon sequestration with high resistance to erosion (Blanco-Canqui et al., 2017). The
dried and sieved samples were milled to a fine powder for 2 min (Laboratory Disc Mill, TeMa Machinery Ltd, UK). For comparison, a few samples were ground by hand with a mortar and pestle, and this yielded similar results. The samples were analysed for carbon as percent mass by a dry oxidative combustion procedure at up to 1000°C using the LECO RC 612 analyser (LECO Corporation (2018); Saint Joseph, Michigan USA), reporting organic carbon, inorganic carbon and total carbon. Ex situ bulk dry soil density was calculated in the laboratory by considering the sieved, dry soil mass obtained on average for the core volume from each soil depth layer. The carbon density was calculated from the carbon content and the ex situ bulk dry soil density. Additionally, soil was analysed for pH. More detail about the soil carbon calculations, pH analysis and the division of soil types is provided as Supporting Information.

Carbon distribution maps were made using ArcMap (version 10.6.1) with geostatistical analysis extension, as explained in Supporting Information. To assess the carbon stored in tree biomass, the parameters such as tree diameter at breast height, height and species were obtained for a total of 117 trees within 6 surveying plots at Cockle Park Farm and another 30 trees at Nafferton Farm. The software package i-Tree (2020) from the United States Department of Agriculture Forest Service, which includes the tools i-Tree Eco and i-Tree Canopy, then enabled quantification of carbon in individual trees, land tree coverage and ultimately the woodland biomass. For comparison with i-Tree Eco, the Woodland Carbon Code: Carbon Assessment Protocol of the Forestry Commission of England (Jenkins et al., 2018) was also used to estimate the carbon storage of trees. The carbon stored by trees in the woodlands was calculated by multiplying the whole area of tree cover obtained from i-Tree Canopy, and the carbon storage of the trial plots obtained from i-Tree Eco. Also, individual trees and small groups of trees grew along field edges and in some fields at the two farms. The crown area of these trees was estimated on satellite images on Google Earth and multiplied by the mean carbon storage of the woodland trees, to calculate their carbon stocks. More detail about the tree biomass carbon surveying methods is provided as Supporting Information. Not all of the soil sampling locations in the woodland were within the plots where biomass was measured. The selected biomass measurement sites only occupied a portion of the woodland.
area (Figures 3 and 4), whereas the soil sampling locations were distributed across the entire woodland area.

To place the results in context, in December 2020 we interviewed the farm director of Newcastle University to understand the current farm management practices and management constraints on options for agricultural land conversion. The interview text is provided in Supporting Information.

2.4 Statistical data analysis of land management effects

Institutional crop rotation records from Gatekeeper (2020), a software package for farm management, a map illustrating land use at Cockle Park farm in approximately 1900 (Shiel, 2000) and other historic maps (Digimap, 2020; MAGIC, 2020) were used to study relationships between land management and terrestrial carbon. At Nafferton Farm, management of agricultural land between 2002 and 2017 also divided the farm into a conventional and an organic system. At Cockle Park Farm, the agricultural land could be classified as either permanent grassland (fields managed for at least 5 years as pastures) or arable land (fields which were ploughed or tilled regularly under crop rotation). The woodland could be classified as either coniferous or broadleaved by polygon areas according to maps on MAGIC. Woodland at Cockle Park Farm could be distinguished according to the time of establishment, which was estimated from historic maps. The responses between means of continuous variables (total carbon, organic carbon density and pH) to variations of independent factors such as land management were tested by the univariate analysis using Tukey’s HSD in SPSS (26.0), and differences were considered significant for a p-value < .05. An Excel spreadsheet was then developed from the field data using the average amount of soil and tree carbon per m² of surface area for each land-use type to predict the total carbon stocks at the two farms as a function of land management. More details about the field data categorization and evaluation are provided as Supporting Information.

3 RESULTS

3.1 Terrestrial carbon stores in agricultural land and woodland at the two university-run farms

The total terrestrial carbon store of the agricultural land (top 90 cm of soil) and woodland (trees and top 90 cm of soil) at the two university-run farms amounted to 103,620 tonnes (Table 1). This carbon store was equivalent to sixteen times the carbon emissions of Newcastle University in the year 2019/20 (6,406 tonnes of CO₂ equivalents-C) (Boot, 2020). Eighty-nine per cent of this carbon store was in the top 90-cm soil layer of agricultural land, with over half of that carbon located in the top 30-cm soil layer (Figure 2). Six per cent of the total terrestrial carbon store was in the top 90 cm of woodland soil. Woodland trees accounted for four per cent, and ‘hedgerow trees’ for one per cent of the total terrestrial carbon store.

3.2 Factors influencing total carbon, organic carbon density and pH in soil

Soil total and organic carbon densities expressed in kg/m³ and soil pH across three soil depths at the two farms, overall, and differentiated according to land use, are summarized in Table 2. TOC accounted for ≥90% of the reported TC. Since soil inorganic C was comparatively small and could reflect geological sources (such as limestone fragments in the parent glacial till), it was not interpreted separately. Generally, total carbon (TC) and total organic carbon (TOC) decreased with soil depth on both farms (one-way ANOVA, p < .001; Table S2), but the differences between the 30- to 60-cm and 60- to 90-cm layers were not statistically significant (Tukey’s HSD in univariate analysis, p > .05; Table S3). Additionally, significant interacted influence caused by soil depth and the classification of fields on the carbon value existed at both farms (one-way ANOVA, p < .01; Table S2). Over the woodland, at least one soil sample was collected in each biomass surveying plot, but with insufficient number for deriving soil carbon for each type of tree coverage (e.g. Figure S7). However, sufficient sampling points were available to compare coniferous and broadleaved woodlands. Consequently, no statistically significant differences in soil carbon densities were observed when comparing soils of broadleaved and coniferous woodland at either farm (one-way ANOVA, p > .05; Table S2).

At Cockle Park Farm, the topsoil of permanent grassland could store more carbon than that of arable land (one-way ANOVA, TC: p = .004; TOC: p = .002; Table S5). At Nafferton Farm, there was no statistically significant difference between organic and conventional management (one-way ANOVA, p > .05; Table S5). At both Nafferton Farm and Cockle Park Farm, higher TC and TOC density was observed in woodland compared with agricultural soil for all depths (one-way ANOVA, p < .05; Table S6). Univariate analysis revealed that the variance for TC and TOC over the woodlands mainly resulted from soil depth rather than farm location, or the combined effect of these two variables (Tukey’s HSD in univariate analysis; Table S4). When comparing soil from a woodland at Cockle Park Farm established after 1960 with soil from a woodland...
established since 1860, the differences in TC and TOC were not statistically significant for any of the soil layers, although a higher mean soil carbon density was found in the older woodland (Table 2). This may reflect that soil carbon increases only incrementally after 40 years of land management as woodland. Note that the woodland age is not necessarily equivalent to tree age because of replanting, and the average tree age estimated from DBH was comparable across the woodlands.

Soil pH increased with the soil depth at both farms (one-way ANOVA, \( p < .001 \); Table S2). Soil pH in agricultural land was generally higher than in woodlands, although a significant trend was only found at Nafferton Farm (one-way ANOVA, \( p < .001 \); Table S2). In each soil profile, pH significantly related to soil total carbon storage on both farms with negative correlation coefficients, except for TC at 60–90 cm (Pearson correlation analysis, \( p < .05 \); Table S7).

### 3.3 Geospatial distribution of total and organic soil carbon

Spatial distribution maps of TC and TOC densities on the two farms illustrate how the woodlands strongly
influenced the overall soil carbon distribution at both farms, and the highest concentration of TC and TOC in all three soil layers was generally measured in the woodlands of both farms (Figures 3 and 4). The agreement between interpolated and measured carbon values is shown in Figures S1–S6. At Cockle Park Farm, the density of TC (kg/m³) and TOC (kg/m³) showed a similar distribution in the 0- to 30-cm and 30- to 60-cm soil layers, being greater in the centre along an east-westerly direction as compared to other places (Figure 3). In the 60- to 90-cm soil layer, the predicted distribution map of carbon showed higher carbon densities in the extreme western parts, whereas lower carbon contents were measured in the centre along a north–south direction at Cockle Park. At Nafferton Farm (Figure 4), a small part on the western agricultural land showed a high carbon density comparable to the

**Table 2** Soil total carbon density (TC, kg/m³; mean ± SD), total organic carbon density (TOC, kg/m³; mean ± SD) and soil pH (mean ± SD) at Cockle Park Farm (CPF) and Nafferton Farm (NF)

| Site       | Land use                | Number of samples | Soil carbon density (kg/m³)      |
|------------|-------------------------|-------------------|----------------------------------|
|            |                         |                   | 0–30 cm                          | 30–60 cm                          |
|            |                         |                   | TC Mean | TC SD | TOC Mean | TOC SD | TC Mean | TC SD | TOC Mean | TOC SD |
| CPF        | Permanent grassland     | 9                 | 24.64   | 7.16  | 23.44    | 6.78   | 8.43    | 2.27  | 7.90    | 2.10  |
| Arable     |                         | 30                | 18.26   | 4.82  | 17.21    | 4.58   | 8.41    | 3.02  | 7.67    | 3.64  |
| Coniferous | woodland               | 10                | 29.49   | 12.68 | 28.21    | 12.43  | 12.47   | 4.78  | 11.71   | 4.62  |
| Broadleaved| woodland               | 6                 | 23.75   | 7.71  | 22.57    | 7.47   | 10.68   | 2.71  | 10.07   | 2.59  |
| Long established | woodland | 10                 | 29.18   | 9.77  | 27.87    | 9.51   | 12.79   | 4.91  | 12.07   | 4.72  |
| Recently established | woodland | 6                 | 24.27   | 13.55 | 23.14    | 13.35  | 10.16   | 1.37  | 9.46    | 1.37  |
| NF         | Permanent grassland     | 2                 | 38.41   | 9.88  | 32.30    | 3.74   | 11.49   | 5.52  | 9.92    | 4.30  |
| Arable     |                         | 29                | 23.08   | 4.96  | 20.96    | 4.43   | 9.07    | 2.54  | 7.83    | 2.50  |
| Coniferous | woodland               | 5                 | 30.37   | 12.28 | 28.69    | 11.96  | 11.83   | 2.07  | 10.86   | 1.69  |
| Broadleaved| woodland               | 11                | 28.39   | 11.44 | 26.54    | 10.79  | 15.35   | 4.59  | 13.90   | 4.61  |
| Conventional |                    | 16                | 25.30   | 7.10  | 22.55    | 5.21   | 9.71    | 3.35  | 8.46    | 2.77  |
| Organic    |                         | 15                | 22.75   | 5.48  | 20.77    | 5.18   | 8.72    | 1.81  | 7.44    | 2.36  |

**Abbreviation:** SD, standard deviation.

† Only one 60–90 cm soil core was sampled at Nafferton Farm permanent grassland because the other one was too compacted to collect.
woodlands. In the 30- to 60-cm soil layer, soil carbon density was again greatest for the woodland sites. As for the 60- to 90-cm soil layer on Nafferton Farm, TC density was the highest in the central part of the farm rather than in the woodlands. In this area of the farm, coal outcrops beneath the soil, and it is likely that fragments of coal have contributed to the determined TOC within the deepest samples.

3.4 Factors influencing carbon stored in woodland trees at the two university-owned farms

Table 3 presents the tree data collected at Cockle Park Farm and Nafferton Farm which include tree species, survey area, DBH, tree height and carbon storage of various tree types processed in i-Tree Eco, and also using the biomass equations of the Woodland Carbon Code (Jenkins et al., 2018). Additionally, it shows the calculated total carbon storage in the woodlands at the two farms. The regression correlation of tree carbon stocks between i-Tree Eco and biomass equations was as follows: $y = 0.87x + 1.39$ ($y$: trees’ carbon stocks from biomass equations; $x$: trees’ carbon stocks from i-Tree Eco; $R^2 = .83$), which showed comparable carbon stock results from two approaches. Across the whole i-Tree dataset, stands of Norway Spruce (15.73 Kg/m²) and Sitka Spruce (15.29 Kg/m²) at Cockle Park Farm exhibited the highest mean C biomass storage, and European Larch stands contributed the lowest C biomass storage (7.03 Kg/m²). According to i-Tree Eco, the average carbon storage on the woodlands at Nafferton Farm was 12.60 Kg/m², slightly higher than the 11.67 Kg/m² at Cockle Park Farm. The tree canopy coverage areas of woodlands at Cockle Park Farm and Nafferton Farm according to i-Tree Canopy were 25 and 13 ha, respectively (Table 3).

3.5 Scenarios for carbon offsetting by terrestrial carbon augmentation in the institutional estate via changes in land management

While most of the terrestrial carbon is currently stored in the agricultural land of the university farms, the woodlands stored significantly more carbon per square metre than the fields (Table 1). The difference between the two land-use types (the subtraction of the mean for agricultural land from the mean for the woodland) was 14.72 kg/m² at Cockle Park Farm and 14.45 kg/m² at Nafferton Farm. Combining the insights gained from the current carbon stock surveys and analysis with the opinions of the farm manager, the total carbon stock for alternative land-use scenarios at the two farms can be estimated in the context of what may or may not be practicable. Totally,

| 60–90 cm | pH |
|----------|----|
| TC Mean  | SD | TOC Mean | SD | 0–30 cm Mean | SD | 30–60 cm Mean | SD | 60–90 cm Mean | SD |
| 7.41     | 1.18 | 6.94 | 1.14 | 6.59 | 0.28 | 7.20 | 0.61 | 7.25 | 0.69 |
| 7.67     | 3.64 | 6.61 | 2.98 | 6.77 | 0.41 | 7.34 | 0.44 | 7.54 | 0.63 |
| 9.03     | 2.30 | 8.46 | 2.20 | 5.12 | 0.85 | 5.53 | 0.70 | 6.03 | 0.68 |
| 9.74     | 2.64 | 9.02 | 2.49 | 4.70 | 0.24 | 5.41 | 0.44 | 6.03 | 0.68 |
| 9.51     | 2.72 | 8.84 | 2.60 | 4.74 | 0.46 | 5.33 | 0.59 | 5.95 | 0.81 |
| 8.94     | 1.82 | 8.38 | 1.68 | 5.33 | 0.93 | 5.75 | 0.57 | 6.15 | 0.30 |
| 7.19     | n.a| 6.15 | n.a| 5.66 | 0.34 | 6.85 | 1.15 | 7.84 | n.a|
| 8.38     | 5.25 | 6.21 | 2.24 | 6.66 | 0.37 | 7.30 | 0.43 | 7.58 | 0.45 |
| 13.27    | 6.68 | 12.27 | 6.50 | 5.60 | 1.20 | 6.69 | 0.60 | 6.51 | 1.04 |
| 10.71    | 2.63 | 9.74 | 2.06 | 5.49 | 0.84 | 6.36 | 1.04 | 6.88 | 0.56 |
| 7.94     | 4.93 | 6.09 | 2.75 | 6.50 | 0.45 | 7.09 | 0.49 | 7.36 | 0.42 |
| 8.82     | 5.60 | 6.36 | 1.34 | 6.69 | 0.41 | 7.47 | 0.40 | 7.88 | 0.28 |

Abbreviation: SD, standard deviation.
†Only one 60–90 cm soil core was sampled at Nafferton Farm permanent grassland because the other one was too compacted to collect.
four scenarios were developed for offsetting a portion of Newcastle University's carbon emissions (CO₂ equivalents-C) by changes in land management on its estate (Tables S8–S11).

Under Scenario 1, if the entire university farm sites were converted to coniferous woodland, an estimated 3,221 tonnes of carbon could be captured and stored per year, over a period of 40 years (Table S8). This number accounts for 50% of the carbon emissions (currently 6,406 tonnes CO₂ equivalents-C per year) caused by the academic activities at the university (Boot, 2020). Converting Nafferton Farm into a forestry research centre with mixed woodland (i.e. 50% coniferous woodland and 50% broadleaved woodland) could offset

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**FIGURE 3** Interpolated maps using Ordinary Kriging for the density distribution of soil total carbon (TC) and total organic carbon (TOC) at Cockle Park Farm

(a) TC 0-30 cm (Kg/m³)
(b) TC 30-60 cm (Kg/m³)
(c) TC 60-90 cm (Kg/m³)
(d) TOC 0-30 cm (Kg/m³)
(e) TOC 30-60 cm (Kg/m³)
(f) TOC 60-90 cm (Kg/m³)
FIGURE 4 Interpolated maps using Ordinary Kriging for the density distribution of soil total carbon (TC) and total organic carbon (TOC) at Nafferton Farm
TABLE 3 Carbon storage (kg/m²) of individual tree species in the fieldwork plots in the woodland, the overall estimated carbon stock (tonnes) of trees in the entire woodland and the estimated carbon stock of ‘hedgerow’ trees at Cockle Park Farm (CPF) and Nafferton Farm (NF)

| Site  | Species                          | Number of trees | Fieldwork plot area (m²) | Average height (m) | Average DBH (cm) | i-Tree total carbon stock (tonnes) | Biomass equations total carbon stock (tonnes) | i-Tree average carbon storage (kg/m²) |
|-------|----------------------------------|-----------------|--------------------------|--------------------|------------------|-----------------------------------|--------------------------------------------|-------------------------------------|
| CPF   | European larch                  | 20              | 583                      | 20.74              | 34.93            | 4.1                               | 6.30                                       | 7.03                                |
|       | Sycamore                         | 20              | 585                      | 21.45              | 34.11            | 7.5                               | 8.61                                       | 12.82                               |
|       | English oak                      | 17              | 1000                     | 24.36              | 36.77            | 9                                 | 11.23                                      | 9                                   |
|       | Sitka spruce                     | 20              | 340                      | 20.01              | 33.32            | 5.2                               | 4.95                                       | 15.29                               |
|       | Norway spruce                    | 20              | 89                       | 15.96              | 17.98            | 1.4                               | 1.09                                       | 15.73                               |
|       | Mix (Sycamore & English Oak)     | 20              | 780                      | 18.35              | 33.31            | 7.9                               | 8.67                                       | 10.13                               |
|       | Sum-entire study area            | 117             | 3377                     | 20.15              | 31.74            | 35.1                              | 40.85                                      | 11.67                               |
| NF    | Mix (Sitka spruce & Norway spruce) | 30              | 1032                     | 18.04              | 41.08            | 13                                | 10.89                                      | 12.60                               |

| Site  | Carbon stock (tonnes) |
|-------|-----------------------|
| CPF   | 3043                  |
| NF    | 1576                  |
| CPF   | 452.7                 |
| NF    | 497.7                 |
29% of these carbon emissions (Scenario 2; Table S9). Alternatively, 64% of these carbon emissions could be offset over a shorter period of about 5 years across the 2 farms, if the agricultural land-use split increased the proportion of permanent grassland relative to arable land to what it used to be around 1900, as illustrated on an old map of Cockle Park Farm (Shiel, 2000) (Scenario 3; Table S10). Finally, by converting at each farm 81.5 ha of arable land (37% at Cockle Park Farm and 19% at Nafferton Farm) into mixed woodland, 10% of these carbon emissions could be offset over a period of 40 years (Table S11).

The outcome of our interview with the farm manager regarding the difficulties of land conversion is summarized in Supporting Information. The soil carbon sequestration approaches discussed included altering the cultivation system, converting arable land back to permanent grassland or woodland, and also biochar application as a way of increasing soil C. From the feedback, various challenges exist, where the two main concerns of the farm manager were the restrictions of the tenancy contract and changes that might affect farm subsidies or tax status. When discussing farm-produced biochar as a carbon sequestration opportunity, it was stated that there were insufficient crop residues being harvested at the two farms, so one would need to purchase biochar from external providers to augment soil carbon, which would increase procurement costs. There were also concerns about the labour hours needed for spreading biochar and inspecting the soil health after adding biochar.

4 | DISCUSSION

Our survey of sixteen carbon management plans from academic institutions in and beyond the UK found that none considered the terrestrial or soil carbon of their estates in a quantitative way (Table S1). Step 1 of the proposed methodological framework (Figure 1) therefore sought to quantify the amount of carbon in the soil and tree biomass using Newcastle University’s rural estate as an example, and it was found that the carbon in soil and tree biomass at its two research farms amounted to sixteen years of institutional carbon emissions. Hence, preserving or augmenting the terrestrial carbon of its estate is quantitatively important for Newcastle University’s institutional carbon management plan. Considering that many other academic institutions in the UK and beyond have larger landholdings than Newcastle University (Barbiroglio, 2018), such findings are of broader significance.

The fieldwork created a valuable database for studying relationships between current and past land use and terrestrial carbon stores (Step 2 in Figure 1). Carbon density in soil was found to be dependent on soil collection depth, different farm locations and land use (woodland vs. agricultural land, and for the latter, permanent grassland vs. arable land at Cockle Park Farm), whereas the woodland vegetation, when the woodlands were established, and conventional vs. organic management practices at Nafferton Farm, had statistically insignificant effects on soil carbon in our data set. The finding that soil carbon storage in agricultural land was less than in woodland is in accordance with other studies (Reynolds et al., 2013; Wang et al., 2019). The negative correlation between soil pH and soil organic carbon storage which was found for the three soil depths at the two farms is also in agreement with previous reports (Minasny et al., 2017; Reynolds et al., 2013). Soil pH is a primary control in environmental microbiology, and microbial processes (including the breakdown of organic matter into CO₂) are slowed down in acidic conditions, while soil pH also controls the carbonate equilibrium (Wiesmeier et al., 2019). Therefore, the relationship between soil pH and carbon content is often found to be significant (Reynolds et al., 2013). The observed lower soil pH under woodland trees as compared to agricultural fields may have contributed to the slower decomposition of soil organic carbon in undisturbed soil (Heikki Martti et al., 2016).

The TC density in the topsoil layer (0–30 cm) of arable land across Cockle Park Farm and Nafferton Farm ranged from 18.26 ± 4.82 kg/m³ to 23.08 ± 4.96 kg/m³, respectively, which are lower than the average value (31.53 Kg/m³) of a 0–15 cm arable soil survey for Great Britain (GB) overall (Reynolds et al., 2013). The mean TOC density over the top 90-cm soil layer in this study (Cockle Park Farm, 12.37 ± 8.10 kg/m³; Nafferton Farm, 13.74 ± 8.99 kg/m³) is lower than the average TOC of woodland, pasture and arable soil (17.56 kg/m³) up to 1 m depth across GB, but similar to the average TOC (14 kg/m³) in England alone (Bradley et al., 2005). At Nafferton Farm, we found similar soil carbon results to Zani et al. (2020) even though the soil sample processing steps and soil carbon determination method differed slightly between the two studies. One reason contributing to the greater amount of carbon of GB soils overall as compared to our results is the occurrence of peat-dominated soils in Wales and Scotland because of higher rainfall, which facilitates carbon sequestration (Balasubramanian et al., 2020; Guo & Gifford, 2002). Average rainfall from 2015 to 2019 was 1147 mm in GB, 902 mm in north-eastern England, 1560 mm in Scotland and 1461 mm in Wales, respectively (Metoffice). When considering the impact of crop types within arable land, our findings showed only minor effects on soil carbon density that are consistent with those of Badagliacca et al. (2018), whereas Wang and Sainju (2014) found that soil carbon is influenced by crop species.
In this study, the division of Nafferton Farm into an organic part and conventional part over fifteen years from 2002 to 2017 had left no significant signature in soil carbon density (afterwards, most of the land was managed conventionally; samples were collected in March 2019). These results differed from those of Gardi et al. (2016) who stated that the soil carbon density would differ for various farming methods. We found higher mean carbon density in the 0–30 cm soil layer of permanent grassland as compared to arable land at both farms, which is consistent with the findings of Balasubramanian et al. (2020) and Gardi et al. (2016). Mean soil carbon density in coniferous woodlands was slightly, but not statistically significantly, higher compared to broad-leaved woodlands on the two farms in this study, and this was also observed for Scottish forest soils (Vanguelova et al., 2013), forest soils in Great Britain (Reynolds et al., 2013) and parkland soils in southern Finland (Heikki Martti et al., 2016). Soil carbon storage for topsoil (0–30 cm) for both broadleaved (mean: 7.82 kg/m²) and coniferous woodlands (mean: 8.98 kg/m²) was slightly higher than the results obtained from the 2007 UK Countryside Survey (CS 2007, at 7.30 kg/m² and 8.14 kg/m², respectively) (Chamberlain et al., 2010; Reynolds et al., 2013). Vanguelova et al. (2013) explained such differences can be due to differences in soil bulk density. A lower bulk density value was used for CS 2007 (0.78 g/cm³ for broadleaved and 0.52 g/cm³ for coniferous) than in this research, which calculated the average bulk density amongst the three soil layers in woodlands as 0.81 g/cm³ for Cockle Park Farm woodland soil and 0.86 g/cm³ for Nafferton Farm woodland soil, respectively. Even if the difference was not statistically significant, an apparent increase in the mean carbon density of the surface soil of woodland at Cockle Park Farm, when comparing the longer established woodland with the more recently established woodland, is of interest. The difference observed is comparable to the range of several studies investigating soil carbon in relation to tree age (Hale et al., 2019; Heikki Martti et al., 2016; Vanguelova et al., 2013). Nevertheless, Hale (2015) also suggested that there was no systematic difference in soil properties between younger and older woodland growth. It should be noted that, even though most of the woodland in this study was over 100 years old, the trees were typically younger, while the soil carbon stock will have accumulated for the life of the woodland, not the individual trees.

Mean biomass C storage (kg/m²) and stocks (tonnes) obtained from i-Tree Eco for the 40-year-old trees in this study (Table 3) were comparable with those of mixed unmanaged growth stands in eastern Wales (65-year-old trees: 7.72–10.65 kg/m², ≥65-year-old trees: 14.09–20.24 kg/m²) (Hale et al., 2019). Only minor differences of tree carbon stocks were observed between the i-Tree Eco and equations in the Carbon Assessment Protocol of the Forestry Commission of England (Woodland Carbon Code). Since i-Tree Eco can be downloaded to smartphones, it enables raw data input directly from the field which is an attractive feature for carbon surveyors.

While the terrestrial carbon findings of this study overall were in good qualitative agreement with the wider literature, the fieldwork established more reliable soil and tree biomass carbon data than could have been inferred from the literature. This is because land management effects on terrestrial carbon will depend on the local climate and geography. In addition, an analysis of the local land-use history as part of step 2 of the proposed methodology (Figure 1) brings generic messages about land management impacts on terrestrial carbon stores closer to home. For example, at Nafferton Farm, the boundary between woodland and agricultural land followed the contours of the Whittle Burn dene, which suggests that the local land-use pattern may have resulted from mediaeval slash and burn agriculture, when woodland was removed to create fields leaving behind woodland only the most inaccessible areas (Ross, 2020). From the data, this mediaeval conversion of woodland into agricultural land would have resulted in a mean terrestrial carbon storage loss of 14.5 kg/m². At Cockle Park Farm, an old map from ~1900 (Shiel, 2000) showed that 84% of the agricultural land was then managed as permanent grassland, and only 16% as arable land, vs. 21% and 79% based on the recent records. According to the data, this land-use change resulted in a carbon loss of 3251 tonnes from the terrestrial carbon stock while Cockle Park Farm was owned and managed by Newcastle University.

Based on analysis of terrestrial carbon stores for current and past land use, one can build realistic proposals for future land-use change to augment the terrestrial carbon stores and thus to offset institutional carbon emissions (CO₂ equivalents-C) (Step 3 in Figure 1). For example, it becomes quickly apparent from Tables S8–S11, which predict the terrestrial carbon stocks as a function of land use on the estate, that substantial land-use changes are required to offset a tangible proportion of Newcastle University’s current carbon emissions (CO₂ equivalents-C) over the next 40 years. According to our research findings, the most effective change to the land management regime would be to convert arable land into new permanent grassland or woodland to sequester carbon in both soils and tree biomass, which is in line with the findings of other studies (Guo & Gifford, 2002; Hallsworth & Thomson, 2017; Rees et al., 2018). Carbon sequestration by converting agricultural land to woodland has been discussed by several other authors (Kaplan et al., 2012; Minasny et al., 2017; Rees et al., 2018). In the UK, the annual amount of carbon removal from land conversion to forestry is 62% higher than for conversion to grassland...
(Hallsworth & Thomson, 2017). On average, the carbon storage in vegetation is lower compared with that in soil (Scharlemann et al., 2014) but mature woods are able to sequester considerably greater carbon than soil does (Hale, 2015).

Except for the conventional land-use transformation, other approaches in terms of increasing soil carbon sequestration are worth researching. According to two long-term experiments at different locations in the south-eastern UK, with a duration of around 160 years, adding farmyard manure can achieve substantial accumulation of soil organic carbon (Poulton et al., 2018). Furthermore, 24 different long-term experiments across southern England over a period of 10 years showed how the application of various organic amendments (e.g. vegetable compost, sewage sludge) increased soil organic carbon at 23 sites (Poulton et al., 2018). Peatland is an ecosystem with the highest carbon density in the terrestrial environment (IUCN, 2018). Peatland covers 10% of the UK land area, and the UK government has taken action on peatland restoration and preservation by sustainable management to maintain or improve the imperative role of peatland in carbon sequestration (IUCN, 2018). Besides, removing CO₂ by enhanced silicate rock weathering in croplands is an attractive technology because of its auxiliary improvement of crop productivity and agricultural soil properties (Beerling et al., 2020), although its effects are difficult to measure. In addition to enhancing the carbon stocks, soil management also needs to consider other important soil characteristics which include the water holding capacity, effect on nutrients, acidification risks (Scharlemann et al., 2014), indirect environmental impacts and financial factors such as labour costs, loss of revenue from crops, the expenditure of purchasing saplings for woodland establishment and the expense of maintenance work. At Newcastle University, although the two farms are not yet part of the institutional carbon management plan, the farm director has developed his own carbon strategy and applied diverse carbon calculation tools to assess their current operations. Moreover, the farm director would like to make more attempts, in cooperation with other departments or companies, to contribute more on carbon abatement (Questionnaire notes in Supporting Information), while also voicing a number of concerns. Likewise, Aggarwal (2020) has debated the various difficulties on implementing a forest carbon project in northern India, involving eight villages with 107 households, and the dominant driving force leading farmers to withdraw from the project was the lack of economic gain. While it is thus acknowledged that land management decisions are made based on multiple additional criteria, the methodological framework developed in this study will help institutions to robustly consider in such decisions the implications on the terrestrial carbon in their estates.

5 | CONCLUSIONS

This study demonstrated that carbon stocks in institutionally owned land can be substantial. Across the top 90 cm soil layer at two farms, woodland soil TC densities were higher compared with agricultural land. In addition, woodland tree biomass carbon storage was 11.67 kg/m² at Cockle Park Farm and 12.60 kg/m² at Nafferton Farm. For the example of Newcastle University, the current carbon stock at its two research farms was 103,620 tonnes in total, equivalent to sixteen years of institutional carbon emissions at the current rate (6,406 tonnes CO₂ equivalents-C per year). By converting 81.5 ha arable land to mixed woodlands (half coniferous and half broadleaved trees) at each farm, 10% of these carbon emissions could be offset over the next 40 years. Various public and private sector institutions have very substantial land ownership and should consider the climate emergency when planning the way in which they manage their land. This study has developed a framework to derive a terrestrial carbon stock estimation by using field surveys, laboratory measurements and ecosystem modelling resources. The methodical framework which has been developed here can provide a perspective to researchers and executives on the realistic scale of updated carbon management plans, which not only quantify current and previous carbon stocks in institutionally managed land, but also consider potential realistic strategies to augment terrestrial carbon stocks in the green space under their management. Meanwhile, the discussions with the farm director reveal an urgent need for more alternatives to increase soil carbon accrual with a range of agricultural carbon abatement practices such as no-tillage, the recycling of organic fertilizers, the application of soil amendments, best management strategies (e.g. high-productivity cultivars with increased plant density), enhanced silicate rock weathering in farming regions and peatland restoration.

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DATA AVAILABILITY STATEMENT
Additional data created during this research are openly available (https://doi.org/10.25405/data.ncl.16782325). Please contact Newcastle Research Data Service at rdm@ncl.ac.uk for access instructions.

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