Geoderma 303 (2017) 19–26

Contents lists available at ScienceDirect

Geoderma

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

Changes in soil C and N stocks and C:N stoichiometry 21 years after land use change on an arable mineral topsoil

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A R T I C L E I N F O

Keywords:
Afforestation
Abandonment
Sequestration
Climate change
Greenhouse gas mitigation
Temperate

A B S T R A C T

The sequestration of excess atmospheric C into resilient and long-lasting belowground pools is of increasing global importance to mitigate greenhouse gas emissions. One land use that is particularly amenable to this type of manipulation is agricultural land, which often has high sequestration potential. However, this capacity can depend on local factors such as cropping history, soil type and climate. Critically, it may also be limited by N availability. In this study we used the retrospective (repeated measures) methodology to assess the impact on previously arable land of land use change by either afforestation with two species of broadleaf trees planted at 800 or 1600 stems ha^{-1} (T800 and T1600), or reversion to rough grassland (NT) for 21 years. We quantified the concentration, distribution and total stocks of organic C and N in the upper 0–30 cm of a common soil type found in NE Scotland and investigated the robustness of C:N to land use change. Finally we estimated ecosystem stocks of C and N, and how these were partitioned between plant and soil components. We found increases in the overall concentrations of soil C from 4.6% to 5.8%, and N from 0.32% to 0.43%. The increase in soil C stocks over the experiment was in the order NT > T800 > T1600 and each treatment differed significantly. The same pattern was seen for increases in N stocks but here the increases in NT and T800 were significantly greater than for T1600. Overall, stocks were higher in the rough grassland plots than under trees by 35 Mg ha^{-1} for C and 2.2 Mg ha^{-1} for N. These increases in stocks were accompanied by a highly significant narrowing in C:N with time across all treatments from 14.6 to 13.6 and differences seen between upper and lower soil layers in 1991 had disappeared by 2012. From an average of 151 Mg ha^{-1} in 1991, the system C stock (soil + plants) had increased to between 202 Mg ha^{-1} (NT) and 221 Mg ha^{-1} (T1600) by 2012, with between 96% (NT) and 73% (T1600) of the C in the soil. Concurrently the system stock of N had increased to between 14.1 Mg ha^{-1} (NT) and 11.3 Mg ha^{-1} (T1600), from an average of 9.4 Mg ha^{-1} in 1991, with between 99% (NT) and 81% (T1600) of the system N in the soil. Although in 2012 there were significantly greater soil C stocks in NT, this was offset by C accumulation in the treatments containing trees, such that overall there were no treatment differences. However, this was not seen with system N stocks in 2012, which were significantly larger in the NT treatment than in those with trees. Mean annual rates of C and N accumulation in the systems were greatest in NT (2.7 and 0.22 Mg ha^{-1} yr^{-1}) and least in T1600 (0.7 and 0.08 Mg ha^{-1} yr^{-1}). These results are important in the context of land use strategies aimed at pollution mitigation, such as C sequestration and nitrate leaching. They are also relevant to the possible effects of land use change, especially reversion to agricultural use, of land previously taken out of production.

1. Introduction

The dynamics of soil organic matter (SOM) continues to represent an active and topical area of research due to the central role it is known to play in ecosystem functioning. As the dominant constituent of SOM, carbon represents one of the most commonly determined of soil attributes with concentrations ranging widely from representing only a minor (< 1.0%) to a major (> 45%) component of surface soils. At any particular time SOM will consist of a diverse heterogeneous mix of compounds with respect to their origin, composition, reactivity and importantly lability (biological availability) and therefore persistence at any particular location. The distribution and total quantities of SOM present within a soil profile reflect a combination of background attributes (e.g., climatic and edaphic) together with more site-specific 'management' factors (e.g., drainage and cropping histories).

Wide-scale and historical changes in land use have therefore had

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http://dx.doi.org/10.1016/j.geoderma.2017.05.002
Received 6 May 2016; Received in revised form 31 March 2017; Accepted 2 May 2017
Available online 11 May 2017
0016-7061/

dramatic influences on the quantity and quality of SOM. Typically, although not exclusively, for temperate regions a change from 'native' to 'agricultural' use has resulted in a loss of SOM (McLauchlan, 2006), which in arable systems can also be associated with a physical redistribution within the soil profile as a result of cultivation and soil mixing (Nierop et al., 2001). An additional consequence of changes to land use can be changes in the elemental composition, type and reactivity of organic compounds. Land use changes that include cultivation, drainage, liming and farming system have dramatically influenced the capacity of soil to act as a sink for C. Kirk and Bellamy (2010) suggested that for the UK, past changes in land use were better able to explain C turnover than recent changes in climate (temperature or moisture). A combination of interacting local factors which broadly equate to the 'soil formation factors' (defined by Jenny, 1941) determine the balance between accumulation and mineralisation of organic matter recently defined as an 'ecosystem property' by Schmidt et al. (2011).

The reversibility of the loss of SOM in agricultural soils by the cessation of ploughing is well established (e.g. Freibauer et al., 2004). It is well demonstrated by the classical long-term studies at Rothamsted (Poulton et al., 2003), which showed the accumulation of SOM and organic C after the removal of arable land from agricultural production (the so-called 'wilderness area'). Interestingly, this study also reported on accompanying changes in total soil N. Reversion of old arable land to woodland resulted in a widening of the C:N ratio as a result of an increase in the quantity of SOC (doubling over 100 years) which was accompanied by a smaller increase in N. The authors suggested that the presence of sufficient 'biologically available' N was a key factor influencing this soil's ability to retain and therefore accumulate SOM. The role that stoichiometric relations between the major nutrients (C:N), which are well-constrained at the global scale, might have with respect to their regulatory influences upon SOM dynamics and average atomic C:N ratios is becoming increasingly recognised (e.g. Cleveland and Liptzin, 2007; Zhao et al., 2015).Similarly, in abandoned agricultural field soils the availability of N appears to control the accumulation of C in abandoned agricultural soils (Knops and Tilman, 2000).

Changing land use influences not only the quantity of C and N likely to be stored in ecosystems but can also influence the physical distribution between above and below ground pools. Where land use changes are substantial, such as those that accompany afforestation of arable land, then the distribution and potential medium term storage of C and N can vary over time. This situation has been highlighted by Sharrow and Ismail (2004) where pastures stored > 90% of their C and N below ground while coniferous plantations had the bulk stored in above ground and litter layers. These authors hypothesized that silvopastoral systems should accumulate more C and N than either grass or tress grown alone. Over the first 11 years these agroforestry plots, located in western Oregon, accumulated 740 and 520 kg ha^{-1} yr^{-1} of C more than forest and pasture respectively, however the N story was not quite so clear.

Here our objective is to quantify the effect of a change in land use from long-term arable into either unmanaged rough grassland or low-density deciduous tree planting after a period of 21 years on the concentration, distribution and total stocks of organic C and N in the upper 0–30 cm of a common soil type found in NE Scotland. In particular we investigate how robust the ratio of C:N is to land use change and the extent to which it may differ between these land uses. Finally we estimate ecosystem stocks of C and N, and how these are partitioned between plant and soil components. Results are considered in relation to land use change strategies aimed at pollution mitigation, such as C sequestration and nitrate leaching.

Table 1
Site characteristics.

Location	57°11.25′ N 2°13.54′ W
Altitude (m)	110–130
Attitude	NE
Slope (%)	0.5
pH	5.6
Soil texture	Sandy loam
Parent material	Granite

2. Methods

2.1. Experimental design

The experiment was established in 1991 at Craibstone Estate, Aberdeen in NE Scotland and basic site characteristics are given in Table 1. The soil is a Dystric cambisol belonging to the Countesswells Association and Countesswells/Terryvale Series (Glentworth and Muir, 1963). It is derived from granitic parent material and imperfectly drained due in part to a semi-continuous indurated (low permeability) soil horizon at a depth of 35–40 cm. The land had previously been in arable cropping for at least 20 years and probably much longer. In each of three sub-blocks, small saplings of sycamore (*Acer pseudoplatanus* L.) and wild cherry (*Prunus avium* L.) were planted by hand at either 800 (T800) or 1600 (T1600) stems ha^{-1} into four plots of 30 m × 37.5 m, plus a 9 m × 60 m area that was not planted (no tree, NT), all surrounded by a 5 m wide guard strip of grass. For the first six years of the experiment each sub-block of four tree + NT plots had one of three different understoreys (ryegrass, white clover or vegetation free), which together formed one experimental block (15 plots). Spatial layout was randomised within blocks, which were replicated three times (45 plots). The understorey treatments were not maintained beyond six years and reverted to a cover of rough grassland (NT plots) or an increasingly negligible cover of rough grassland/leaf litter (T plots) for the remaining 15 years. Both understorey and trees were not managed during this period although they were subject to low levels of grazing and browsing by wild animals. Meteorological data were obtained from a weather station at Craibstone, about 0.5 km from the study site (Fig. 1).

2.2. Sampling and analyses

Before the trees were planted in spring 1991 and again in spring 2012, 10 soil cores (3.5 cm diameter) were taken per plot after removal

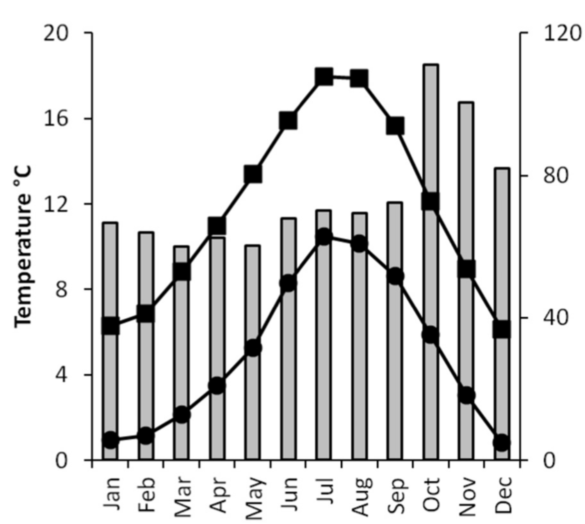

Fig. 1. Mean monthly maximum (squares) and minimum (circles) air temperatures and mean total monthly rainfall recorded 0.5 km from the study site for 1991–2012.