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Research paper

An empirical model approach for assessing soil organic carbon stock changes following biomass crop establishment in Britain

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ABSTRACT

Land-use change (LUC) is a major influence on soil organic carbon (SOC) stocks and the global carbon cycle. LUC from conventional agricultural to biomass crops has increased in Britain but there is limited understanding of the effects on SOC stocks. Results from paired plot studies investigating site-specific effects document both increasing and decreasing SOC stocks over time. Such variation demonstrates the sensitivity of SOC to many factors including environmental conditions. Using a chronosequence of 93 biomass crop sites in England and Wales, mainly of 1–14 y age, empirical models were developed of SOC trajectory following LUC from arable and grassland to short rotation coppice (SRC) willow and *Miscanthus* production. SOC stocks were calculated for each site using a fixed sampling depth of 30 cm and changes were estimated by comparing with typical pre-conversion SOC stocks. Most LUCs had no demonstrable net effect on SOC stocks. An estimated net SOC loss of 45.2 ± 24.1 tonnes per hectare (±95% confidence intervals) occurred after 14 y following LUC from grassland to SRC willow. Soil texture and climate data for each site were included in multivariable models to assess the influence of different environmental conditions on SOC trajectory. In most cases the addition of explanatory variables improved the model fit. These models may provide some preliminary estimates of more region-specific changes in SOC following LUC. However, the model fit did not improve sufficiently as to provide a basis for adopting a more targeted LUC strategy for lignocellulosic biomass crop production.

1. Introduction

Soils globally represent the most significant long term organic carbon store in terrestrial ecosystems, containing 4.5 times as much carbon (C) as all living biomass [1] and 3.1 times as much as the atmosphere [2]. Soil organic carbon (SOC) storage results from a dynamic equilibrium between C continuously entering the soil through organic matter inputs and leaving through decomposition and mineralisation, dissolved organic carbon leaching and erosion. Land-use change (LUC) from natural to agro-ecosystems has a major impact on this balance and is the second largest source of anthropogenic greenhouse gas (GHG) emissions after fossil fuel combustion [3]. This vulnerability to human impact is recognised in Articles 3.3 and 3.4 of the Kyoto Protocol with signatory states required to report SOC stock changes resulting from LUC in their annual GHG inventories. Consequently, efforts are being made to identify land-uses that increase SOC storage and utilise the C sink capacity offered globally through agricultural and degraded soils [4,5].

LUC from conventional agriculture to purpose-grown lignocellulosic biomass crop production has become increasingly common in Europe [6]. It has been argued that using land as a source for bioenergy crops has the potential to offset anthropogenic CO_2 emissions through soil C sequestration as well as fossil fuel substitution [4,7]. Purpose-grown biomass crops have been promoted as a source of lignocellulosic feedstock for the production of heat and electricity as well as for the future production of liquid biofuels [8]. It has been suggested that lignocellulosic biomass crops are a more sustainable resource than using food crop-based biofuels [9–11]. Studies indicate that lignocellulosic biomass crops require fewer inputs and can grow on marginal land [7,12,13] but concerns remain over competing land-use where purpose-grown biomass crops will replace food production.

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Miscanthus x *giganteus* and short-rotation coppice *Salix* spp. (SRC willow) are the most prevalent lignocellulosic biomass crops in the UK and currently cover estimated areas of 79–135 km^2 and 22–55 km^2 respectively [6,14,15]. However, this is expected to increase, with 9,300–36,300 km^2 of land being identified as available for lignocellulosic biomass crop production in the UK [16]. Although life-cycle assessments indicate *Miscanthus* and SRC willow have significant potential for GHG mitigation through fossil fuel substitution [7], an absence of data relating to the effects of LUC on SOC and biogenic GHG emissions remains a barrier to their promotion through policy formulation [17].

The effects of LUC on SOC stocks are difficult to assess and long term monitoring of SOC stocks through repeated assessment of soil inventories is time-consuming and complex, often showing insignificant changes in SOC or inconsistent temporal and spatial trends [18–21]. The potential to measure changes in SOC over time is limited with detectability dependent on the number of samples taken as well as the rate of change [22,23]. Attempts have been made to develop simple and cost-effective practical indicators of SOC stock changes that would avoid repeated sampling [24,25]. However, such measurements have not been widely tested and require validation for a range of soil and land-use types. Due to the many problems associated with long term measurements, space-for-time substitution methods are preferred to infer the effects of LUC over time.

Results of paired plot studies investigating effects of land conversion to lignocellulosic biomass crops on SOC stocks often report short term gains in SOC following the conversion of arable land to *Miscanthus* in temperate Europe [26–28] while losses and gains have both been inferred for LUC from arable crops to SRC willow [29]. Studies typically infer no significant change in SOC following the conversion of grassland to *Miscanthus* [26,30,31], and a loss of SOC following LUC from grassland to SRC willow [29,32]. However, the trajectory and magnitude of change differs between studies, reflecting the general sensitivity of SOC to site-specific factors such as climate, soil texture, crop management, previous land-use and SOC stocks [33]. A large number of study sites representing LUC under a range of conditions would be required to ascertain the overall net effect of LUC on a landscape scale.

The carbon response function (CRF) concept was developed as a simple statistical tool to describe the relative SOC change rate after LUC as a function of time [34]. With this approach, SOC stock changes (ΔSOC%) are inferred using reference sites and regression models are fitted to the dataset with the best-fit model, or 'general carbon response function' (CRF_{gen}), identified to provide an overall measure of change across multiple sites [35]. To investigate the influence of environmental parameters on SOC change rate and to improve the model fit, additional variables are used in a multivariable model designated 'specific carbon response function' (CRF_{spec}) for the purpose of more region-specific estimates [35,36]. These empirical models are more transparent and less complex than process-based simulation models although they require large datasets to provide reliable estimates of temporal trends in SOC following LUC.

CRF models have been developed to estimate the effects of major LUCs in temperate Europe [36,37]. For these historic LUCs large retrospective datasets were available from which paired sites that were adjacently situated could be selected to ensure similar pedological conditions. However, in circumstances where suitable reference sites were unavailable and rather than limiting the number of study sites, average pre-conversion SOC stocks obtained from soil surveys have been employed to provide a baseline measurement with which to estimate relative changes in SOC [37]. This method has also been employed in the present study to assess the impact of LUC for lignocellulosic biomass crop production, since this is a recently emerging LUC in Britain and we were subsequently constrained by a lack of retrospective datasets and suitable reference sites. Here two approaches have been combined to assess SOC trajectory following biomass crop establishment: (i) free-intercept models were used to determine the post-conversion trajectory of SOC for a selection of sites that can be assumed to follow a similar trajectory and; (ii) forced-intercept CRFs were developed to estimate net changes in SOC from a hypothetical baseline and to assess the effects of environmental parameters on SOC changes. The main purpose is to assist in targeting future research efforts and to provide preliminary evidence for policy makers.

2. Materials and methods

2.1. Site selection

A list of 150 commercial SRC willow and 121 *Miscanthus* plantations was compiled in England and Wales, from which 45 SRC willow and 48 *Miscanthus* plantations were selected for soil sampling. To limit variance arising from site-specific factors the following were excluded from the list: (i) sites with anomalously high SOC content (>8% SOC) or wetland soil, (ii) crops established on reclaimed land, and (iii) land where organic fertiliser (sewage sludge or manure) had been applied in the five years prior to sampling. Of those remaining, 93 sites were selected to obtain as far as possible a broad, even range of age and an equal representation of SRC willow and *Miscanthus* plantations established on arable and permanent grassland. Due to the relatively recent emergence of these crops as a biomass resource in Europe, all plantations were between 1 and 14 y old at the time of sampling, apart from one plantation, a 22-y old SRC willow crop. The number of plantations established on former grassland sites was limited, owing to declining policy support. All available conversions from permanent grassland were sampled and supplemented by sites comprising set-aside fields that had been under grassland management for at least five years prior.

Sites from each crop type were generally located in the same broad geographical area (Fig. 1) with similar climatic characteristics and soil texture to ensure similar site trajectory (Table 1). Site climate was categorised using mean annual precipitation (MAP) and mean annual temperature (MAT), based on 1981–2010 observations, obtained for the Met Office weather station closest to each study site. Soil texture at 26% of the sites was 'light' (<15% clay), 70% of sites had 'medium' texture (15–30% clay) and 4% were 'heavy' textured (>30% clay). All sites fall within a range of 10–38% clay content. The distribution of sites was affected by historic planting efforts, with a concentration towards the north-east and south-west of England (Fig. 1). To reduce bias only one field was sampled on a given farm, even if another stand age was present.

2.2. Soil sampling

Soil sampling at the 93 study sites was undertaken between March and November 2011. Each field was divided into a grid of 100 intersections of which 25 were randomly selected for sampling. Soil cores (30 mm diam.) were taken to 30 cm depth and divided into two layers (0–15 and 15–30 cm). Where roots or large stones were present, the sample was taken from within 10 cm of the grid intersection. Samples were combined by depth and stored at 4 °C for a maximum of 2 weeks before processing for analysis. Three additional cores of 50 mm diam. were taken to 15 cm depth from randomly selected intersections, using a specialised ring corer kit to measure soil bulk density (BD) (Van Walt, Haslemere, England).