Evaluation of the ECOSSE model for simulating soil organic carbon under *Miscanthus* and short rotation coppice-willow crops in Britain

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Abstract

In this paper, we focus on the impact on soil organic carbon (SOC) of two dedicated energy crops: perennial grass *Miscanthus x Giganteus* (*Miscanthus*) and short rotation coppice (SRC)-willow. The amount of SOC sequestered in the soil is a function of site-specific factors including soil texture, management practices, initial SOC levels and climate; for these reasons, both losses and gains in SOC were observed in previous *Miscanthus* and SRC-willow studies. The ECOSSE model was developed to simulate soil C dynamics and greenhouse gas emissions in mineral and organic soils. The performance of ECOSSE has already been tested at site level to simulate the impacts of land-use change to short rotation forestry (SRF) on SOC. However, it has not been extensively evaluated under other bioenergy plantations, such as *Miscanthus* and SRC-willow. Twenty-nine locations in the United Kingdom, comprising 19 paired transitions to SRC-willow and 20 paired transitions to *Miscanthus*, were selected to evaluate the performance of ECOSSE in predicting SOC and SOC change from conventional systems (arable and grassland) to these selected bioenergy crops. The results of the present work revealed a strong correlation between modelled and measured SOC and SOC change after transition to *Miscanthus* and SRC-willow plantations, at two soil depths (0–30 and 0–100 cm), as well as the absence of significant bias in the model. Moreover, model error was within (i.e. not significantly larger than) the measurement error. The high degrees of association and coincidence with measured SOC under *Miscanthus* and SRC-willow plantations in the United Kingdom, provide confidence in using this process-based model for quantitatively predicting the impacts of future land use on SOC, at site level as well as at national level.

Keywords: ECOSSE model, energy crops, land-use change, *Miscanthus*, process-based model, short rotation coppice-willow, soil organic carbon

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Introduction

The European renewable energy directive 2009/28/EC (E.C., 2009) provides a legislative framework for reducing greenhouse gas (GHG) emissions by 20%, while achieving a 20% share of energy from renewable sources by 2020. Energy crops can contribute to both targets by replacing fossil fuel energy sources, as well as increasing soil organic carbon (SOC) sequestration, that is the long-term storage of carbon (C) in soil (Clifton-Brown et al., 2004). In this paper, we focus on the impact on SOC of two dedicated energy crops: short rotation coppice (SRC)-willow and perennial grass *Miscanthus x Giganteus* (*Miscanthus*).

Short rotation coppicing is a system of semi-intensive cultivation of fast-growing, woody species. The rotations between harvests are short (3–4 years) in comparison with longer rotations in typical forests (Don et al., 2012), and the frequent harvests enhance root turnover (Block et al., 2006). Annual leaf litter in Europe has been estimated to be on average between 1 and 5 t ha−1 (Baum et al., 2009); therefore, inputs of organic matter to soils under SRC are assumed to be relatively high compared to conventional crops. Moreover, no tillage is required during the lifetime of SRC which may enhance SOC sequestration (West & Post, 2002; Walter et al., 2015).

Short rotation coppicing of willow has a high potential to increase SOC due to the abundant above- and belowground biomass input. For example, a study by Tufekcioglu et al. (2003) reported that willow trees in...
Iowa, USA, can have greater productivity of fine root biomass than corn (5.8 t ha\(^{-1}\) vs. 0.9 t ha\(^{-1}\) for corn, 7 years after establishment). Zan et al. (2001) established a factorial experiment with 4-year-old energy plantations in south-western Quebec, Canada. They reported an average SOC sequestration at 0–60 cm soil depth across sites, not including belowground biomass, of 130 t C ha\(^{-1}\) following planting of willow, compared to 110 t C ha\(^{-1}\) measured in soil on abandoned agricultural fields used as a baseline for comparison and therefore an estimated SOC sequestration rate under willow of approximately 4 t C ha\(^{-1}\) yr\(^{-1}\).

In a study of three mixed poplar, aspen and willow plantation sites across Germany, a small increase in SOC (45 and 44 t C ha\(^{-1}\), under current vegetation and former arable soils, respectively) of 0.1–0.6 t C ha\(^{-1}\) yr\(^{-1}\) in the upper 30 cm soil was observed after 7 years of transition from former arable soil (Jug et al., 1999; Meki et al., 2014).

In the United Kingdom, SRC-willow has been identified as the bioenergy crop with the greatest potential for C mitigation across the United Kingdom (Smith et al., 2000a,b). Willow is an ideal species for SRC in the United Kingdom because of its vigorous shoot regeneration after coppicing, and its suitability to regional climate and soil conditions (Britt et al., 1995; Grogan & Matthews, 2002). Grogan & Matthews (2002) estimated a SOC sequestration rate to 50 cm soil depth of 0.5 t C ha\(^{-1}\) yr\(^{-1}\) under SRC-willow plantations in the United Kingdom. They developed a model to characterize the essential processes underlying SOC dynamics relating to SOC sequestration but stressed the need for further model development to account for the dynamics of the system within each season, as well as for regional variations in yield and soil C inputs and outputs.

Miscanthus is one of the most promising dedicated energy crops with around 16 000 ha being established in the United Kingdom (Don et al., 2012). Several features of Miscanthus’ physiology and the agricultural practices associated with its cultivation suggest a large potential for SOC sequestration (Dondini et al., 2009a). Miscanthus is usually harvested in spring to allow winter senescence to reduce plant moisture content. Leaving the crop standing over winter increases litter fall, leading to the accumulation of biomass on the soil surface (Zimmermann et al., 2013). In addition, as a rhizomatous crop it allocates a large proportion of the aboveground C to the roots and rhizomes during winter senescence, further increasing SOC stocks (Kuzyakov & Domanski, 2000). When Miscanthus is planted on former arable land, the absence of soil tillage results in less soil disturbance which, in turn, enhances SOC stabilization processes (Clifton-Brown et al., 2007).

The amount of SOC sequestered by Miscanthus is a function of site-specific factors including soil texture, management practices, initial SOC levels and climate (Lemus & Lal, 2005); for these reasons, both losses and gains in SOC were observed in Miscanthus studies (Hansen et al., 2004; Clifton-Brown et al., 2007). Several studies quantifying the changes in SOC on converting arable land to Miscanthus energy crop reported an increase in SOC; the reported SOC change rate, however, varied largely across and within experiments, ranging from 0.8 to 2.8 t C ha\(^{-1}\) yr\(^{-1}\) (Kahle et al., 1999; Hansen et al., 2004; Dondini et al., 2009a;b; Zimmermann et al., 2011; Felten & Emmerling, 2012). Changes from pasture to a Miscanthus energy crop have a small effect on SOC. In a review of the effect of land-use change to bioenergy production in Europe, Don et al. (2012) estimated a SOC change of −0.09 t C ha\(^{-1}\) yr\(^{-1}\) if grassland was converted to Miscanthus. On the other hand, Zatta et al. (2014) reported that planting on semipermanent grasslands with a range of Miscanthus genotypes did not deplete SOC significantly after 6 years from establishment. Moreover, the authors suggested that it is highly unlikely that a reduction in SOC levels relative to initial values with increasing stand age will occur.

Methods for the determination of SOC involve direct and indirect approaches. Direct methods employ field and laboratory measurements of SOC stocks, but field documentation of SOC changes faces many challenges because of the heterogeneity of soils, environmental conditions, land-use history, sampling methods and analytical errors. Therefore, indirect methods, which require the use of process-based models, are used to predict SOC changes temporally and spatially (Saby et al., 2008). Computer models can also complement and extend the applicability of information collected in field trials (Meki et al., 2013). Combining measurement of SOC with models also provides a useful tool to test the model performance to simulate soil processes with a higher degree of confidence. In fact, model evaluation involves running a model using input values that have not been used during the calibration process, demonstrating that it is capable of making accurate simulations on a wide range of conditions (Moriasi et al., 2007). Although several soil C models have been developed for conventional agricultural and forest systems, most of them have not been fully parameterized and effectively tested for application on Miscanthus and SRC-willow (Dimitriou et al., 2012; Borzecka-Walker et al., 2013; Robertson et al., 2015). Here we focus on the applicability of the process-based model ECOSSE to predict SOC sequestration and SOC changes after transition to Miscanthus and SRC-willow.

The development of the ECOSSE model was mainly due to the need to simulate the C and nitrogen (N)
cycles using minimal input data on both mineral and organic soils (Smith et al., 2010a,b). The ECOSSE model has already been validated and applied spatially to simulate land-use change impacts on SOC and GHG emissions over different soil types, to simulate SOC change under energy crops and to simulate soil N and nitrous oxide (N\textsubscript{2}O) emissions in cropland sites in Europe (Smith et al., 2010b; Bell et al., 2012). It has also been previously evaluated against a range of soils under short rotation forestry (SRF) plantations across the United Kingdom (Dondini et al., 2015).

This paper evaluates the suitability of ECOSSE for estimating SOC sequestration from SRC-willow and Miscanthus soils in the United Kingdom after land-use change from conventional systems (grassland and arable). Based on the previous published recommendations, a combination of graphical techniques and error index statistics have been used for model evaluation (Moriai et al., 2007). Model testing is often limited by the lack of field data to which the simulations can be compared (Desjardins et al., 2010) and by inconsistent sampling approaches and soil depths. In this study, the model is evaluated against observations at 29 locations in the United Kingdom, comprising 19 paired transitions to SRC-willow and 20 paired transitions to Miscanthus, and two soil depths (0–30 and 0–100 cm), meaning that the mechanistic processes of ECOSSE can be thoroughly evaluated.

Materials and methods

ECOSSE model

The ECOSSE model includes five pools of soil organic matter (SOM), each decomposing with a specific rate constant. Decomposition is sensitive to temperature, soil moisture and vegetation cover, and so soil temperature, pH, bulk density and clay content of the soil along with land-use and monthly climate data are the inputs to the model (Coleman & Jenkinson, 1996; Smith et al., 1997). The ECOSSE model simulates the C and N cycles for six categories of vegetation: arable, grassland, forestry, and seminatural, SRC-Willow and Miscanthus.

The soil input of the vegetation (SI) is estimated by a modification of the Miami model (Lieth, 1972), which is a simple conceptual model that links the climatic net primary production of biomass (NPP) to annual mean temperature (T) and total precipitation (P) (Grieser et al., 2006). Separate estimates are obtained for NPP as a function of temperature and precipitation according to empirical relationships, and the Miami estimate of NPP is found as the minimum of these two estimates. The NPP estimated by the Miami model is then rescaled for each land-cover type. The scaling factor for Miscanthus (1.6) was calculated as the ratio of mean UK yield estimated using Miscanfor (Hastings et al., 2014), converted to NPP, to mean UK NPP estimated by Miami. The scaling factor for SRC-willow (0.875) was calculated by adjusting the Miscanthus scaling factor by the ratio of SRC-willow yield values (Styles et al., 2008) to Miscanthus yield values. SI is then estimated as a fixed proportion of the rescaled NPP according to the land cover, as described by Schulze et al. (2010). The linear rescaling of the nonlinear Miami functions is reasonable given the near-linear behaviour of the Miami functions in the temperature and precipitation range of the United Kingdom. The NPP estimated by the Miami model is a function of climatic variables only; therefore, it does not capture the effects of other local environmental factors such as N inputs. However, the rescaling factors derived for each land-use type implicitly account for standard management practices. For a full description of the ECOSSE model, refer to Smith et al. (2010a).

The minimum ECOSSE input requirements for site-specific simulations are as follows:

- Thirty years of average monthly rainfall, potential evapotranspiration (PET) and temperature and
- Monthly rainfall and temperature.

### Soil data:
- Initial SOC content,
- Soil sand, silt and clay content,
- Soil bulk density,
- Soil pH and
- Soil depth.

### Land-use data:
- Land use for each simulation year.

The initialization of the model is based on the assumption that the SOC is at steady state under the initial land use at the start of the simulation. Previous work has used SOC measured at steady state to determine the plant inputs that would be required to achieve an equivalent simulated value (e.g. Smith et al., 2010a). This approach iteratively adjusts plant inputs until measured and simulated values of SOC converge. Running the simulations to steady state with this adjusted rate of plant input therefore provides an estimate of the activity of the SOM as expressed by the relative C pool sizes of the decomposable plant material, resistant plant material, microbial biomass (BIO) and humified organic matter. However, where input data are missing, most notably the description of the drainage of the soil, the OM in soil with restricted drainage is actually decomposing more slowly than would be calculated from the available soil descriptors. This results in an unrealistically high estimate of plant inputs to compensate for the elevated simulated decomposition rate. In the absence of additional measurements, estimates of plant inputs from the NPP model Miami (Lieth, 1972, 1973) can be used to account for rate modifiers that are missing due to the lack of input data. This approach instead fixes the plant inputs at the rate estimated by the Miami model and then iteratively adjusts an additional decomposition rate modifier until the SOC simulated using the Miami model converges with the measured value. The same rate modifier is used for all pools, so this approach is adjusting the overall activity of the SOM to account for the missing input data, not the rate constants of the pools, which
Table 1 Details of vegetation type, duration between establishment and sampling, and location of the study sites

| Site no. | Transitions (previous land use in bold) | Latitude, Longitude | Duration between establishment and sampling (years) |
|----------|----------------------------------------|---------------------|---------------------------------------------------|
| 1        | SRC-willow                             | 53.7, −0.8          | 5                                                 |
| 2        | SRC-willow                             | 52.2, −0.5          | 12                                                |
| 1 + 2C   | SRC-willow                             | 52.2, −0.5          | 20+                                               |
| 3        | SRC-willow                             | 53.2, −0.8          | 11                                                |
| 4        | SRC-willow                             | 52.5, −0.6          | 7                                                 |
| 4C       | SRC-willow                             | 52.2, −0.7          | 20+                                               |
| 5        | SRC-willow                             | 54.6, −2.6          | 20+                                               |
| 5C       | Grassland                              | 54.0, −1.2          | 32                                                |
| 6        | SRC-willow                             | 54.1, −1.1          | 7                                                 |
| 6C       | SRC-willow                             | 53.4, −0.5          | 12                                                |
| 7        | SRC-willow                             | 52.5, −0.8          | 20+                                               |
| 7C       | Grassland                              | 52.0, −0.1          | 7                                                 |
| 8        | SRC-willow                             | 51.5, −0.8          | 6                                                 |
| 8C       | Grassland                              | 51.5, −1.3          | 100 cm soil depth. In total, 12 arable to SRC-willow transitions, 11 arable to Miscanthus transitions and nine grassland to Miscanthus transitions were sampled (Table 1). |
| 9        | Miscanthus                             | 51.5, −1.6          | 6                                                 |
| 10       | Miscanthus                             | 51.5, −1.6          | 6                                                 |
| 9 + 10C  | Miscanthus                             | 51.5, −1.6          | 6                                                 |
| 11       | SRC-willow                             | 54.1, −1.1          | 6                                                 |
| 11C      | Miscanthus                             | 52.5, −0.5          | 2                                                 |
| 12       | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 12C      | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 13       | Grassland                              | 52.5, −0.8          | 20+                                               |
| 13C      | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 14       | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 14C      | Grassland                              | 52.5, −0.8          | 20+                                               |
| 15       | SRC-willow                             | 52.5, −0.8          | 20+                                               |
| 15C      | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 16       | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 16C      | Grassland                              | 52.5, −0.8          | 20+                                               |
| 17       | SRC-willow                             | 52.5, −0.8          | 20+                                               |
| 17C      | Grassland                              | 52.5, −0.8          | 20+                                               |
| 18       | SRC-willow                             | 52.5, −0.8          | 20+                                               |
| 18C      | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 19       | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 19C      | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 20       | SRC-willow                             | 52.5, −0.8          | 20+                                               |
| 22       | SRC-willow                             | 52.5, −0.8          | 20+                                               |
| 20, 22C  | Grassland                              | 52.5, −0.8          | 20+                                               |
| 23       | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 23C      | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 24       | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 24C      | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 25       | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 25C      | Grassland                              | 52.5, −0.8          | 20+                                               |
| 26       | SRC-willow                             | 52.5, −0.8          | 20+                                               |
| 26C      | SRC-willow                             | 52.5, −0.8          | 20+                                               |
| 27       | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 27C      | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 28       | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 28C      | Grassland                              | 52.5, −0.8          | 20+                                               |
| 29       | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 29C      | Grassland                              | 52.5, −0.8          | 20+                                               |
| 30       | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 30C      | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 31       | Miscanthus                             | 52.5, −0.8          | 20+                                               |
| 31C      | Pasture                               | 52.5, −0.8          | 20+                                               |

Table 1 (continued)

| Site no. | Transitions (previous land use in bold) | Latitude, Longitude | Duration between establishment and sampling (years) |
|----------|----------------------------------------|---------------------|---------------------------------------------------|
| 33       | SRC-willow                             | 56.0, −3.6          | 14                                                |
| 33C      | Arable                                 | 56.2, −3.2          | 6                                                 |
| 34       | SRC-willow                             | 56.2, −3.2          | 6                                                 |
| 34C      | Grassland                              | 56.2, −3.2          | 6                                                 |
| 35       | SRC-willow                             | 56.2, −3.2          | 6                                                 |
| 35C      | Grassland                              | 56.2, −3.2          | 6                                                 |
| 36       | Miscanthus                             | 56.2, −3.2          | 6                                                 |
| 36C      | Arable                                 | 56.2, −3.2          | 6                                                 |
| 37       | SRC-willow                             | 56.2, −3.2          | 6                                                 |
| 37C      | Arable                                 | 56.2, −3.2          | 6                                                 |
| 38       | Miscanthus                             | 56.2, −3.2          | 6                                                 |
| 38C      | Grassland                              | 56.2, −3.2          | 6                                                 |
| 39       | Miscanthus                             | 56.2, −3.2          | 6                                                 |
| 39C      | Arable                                 | 56.2, −3.2          | 6                                                 |
| 40       | Miscanthus                             | 56.2, −3.2          | 6                                                 |
| 40C      | Arable                                 | 56.2, −3.2          | 6                                                 |
| 41       | SRC-willow                             | 56.2, −3.2          | 6                                                 |
| 42       | Miscanthus                             | 56.2, −3.2          | 6                                                 |
| 41/42C  | Miscanthus                             | 56.2, −3.2          | 6                                                 |

SRC, short rotation coppice.

remains a fixed characteristic of the model. The rate modifier calculated in this way is then used unchanged for any subsequent calculations to determine the impact of changes in land use. Here we are testing a modelling approach that can also be applied at large scales, so rather than measuring additional values at the specific sites, we used the above approach to evaluate the model using only the input data that would be available in large-scale simulations.

Data

In 2012/2013, 29 sites, including a total of 40 transitions, were sampled in Britain using a paired site comparison approach (Keith et al., 2015). The sites and the relative measurements contribute to the ELUM (Ecosystem Land Use Modelling & Soil Carbon GHG Flux Trial) project, which was commissioned and funded by the Energy Technologies Institute (ETI). Each transition consisted of one reference field (arable or grassland, depending on the previous land use of the site) and one adjacent bioenergy field (Miscanthus or SRC-willow); some sites contained multiple transitions. At each site, soil samples were collected at two soil depths, for a total of 40 transitions sampled at 0–30 cm soil depth and 38 transitions sampled at 0–100 cm soil depth. In total, 12 arable to SRC-willow transitions, eight grassland to SRC-willow transitions, 11 arable to Miscanthus transitions and nine grassland to Miscanthus transitions were sampled (Table 1).

The soil of each bioenergy plantation or control field was sampled using a hierarchical design (Keith et al., 2015), developed to capture variability across different spatial scales (Conant & Paustian, 2002; Conant et al., 2003). Five sampling plots per field were randomly selected, and three soil cores...
Table 2: Long-term (30 years) monthly rainfall and temperature at the location of the study sites. Monthly rainfall and temperature were extracted from the E-OBS data set (Haylock et al., 2008; http://eca.knmi.nl/). Monthly PET was estimated using the Thornthwaite method (Thornthwaite, 1948).

| Site code | Rainfall (mm month\(^{-1}\)) | Temperature (°C) |
|-----------|-------------------------------|-----------------|
|           | January                       | February        |
| 1         | 52                            | 3.9             |
| 2         | 49                            | 4.2             |
| 3         | 139                           | 4.1             |
| 4         | 80                            | 4.2             |
| 5         | 56                            | 4.3             |
| 6         | 57                            | 4.2             |
| 7         | 57                            | 4.3             |
| 8         | 48                            | 4.3             |
| 9         | 51                            | 4.2             |
| 10        | 63                            | 4.0             |
| 11        | 58                            | 4.1             |
| 12        | 64                            | 4.1             |
| 13        | 64                            | 4.1             |
| 14        | 65                            | 4.1             |
| 15        | 128                           | 4.2             |
| 16        | 152                           | 4.2             |
| 17        | 78                            | 4.0             |
| 18        | 84                            | 4.0             |
| 19        | 85                            | 4.0             |
| 20        | 116                           | 4.0             |
| 21        | 111                           | 4.0             |
| 22        | 107                           | 4.0             |
| 23        | 96                            | 4.0             |
| 24        | 90                            | 4.0             |
| 25        | 104                           | 4.0             |
| 26        | 63                            | 3.9             |
| 27        | 63                            | 3.9             |
| 28        | 56                            | 3.9             |
| 29        | 64                            | 3.9             |
| 30        | 63                            | 3.9             |
| 31        | 65                            | 3.9             |
| 32        | 128                           | 3.9             |
| 33        | 152                           | 3.9             |
| 34        | 78                            | 3.9             |
| 35        | 84                            | 3.9             |
| 36        | 85                            | 3.9             |
| 37        | 116                           | 3.9             |
| 38        | 111                           | 3.9             |
| 39        | 107                           | 3.9             |
| 40        | 96                            | 3.9             |
| 41        | 90                            | 3.9             |
|           | February                       | March           |
| 1         | 40                            | 3.6             |
| 2         | 38                            | 3.6             |
| 3         | 99                            | 3.6             |
| 4         | 53                            | 3.6             |
| 5         | 42                            | 3.6             |
| 6         | 41                            | 3.6             |
| 7         | 41                            | 3.6             |
| 8         | 37                            | 3.6             |
| 9         | 37                            | 3.6             |
| 10        | 45                            | 3.6             |
| 11        | 43                            | 3.6             |
| 12        | 41                            | 3.6             |
| 13        | 45                            | 3.6             |
| 14        | 43                            | 3.6             |
| 15        | 41                            | 3.6             |
| 16        | 43                            | 3.6             |
| 17        | 41                            | 3.6             |
| 18        | 45                            | 3.6             |
| 19        | 45                            | 3.6             |
| 20        | 43                            | 3.6             |
| 21        | 41                            | 3.6             |
| 22        | 45                            | 3.6             |
| 23        | 45                            | 3.6             |
| 24        | 41                            | 3.6             |
| 25        | 43                            | 3.6             |
| 26        | 41                            | 3.6             |
| 27        | 43                            | 3.6             |
| 28        | 41                            | 3.6             |
| 29        | 45                            | 3.6             |
| 30        | 41                            | 3.6             |
| 31        | 45                            | 3.6             |
| 32        | 43                            | 3.6             |
| 33        | 41                            | 3.6             |
| 34        | 43                            | 3.6             |
| 35        | 41                            | 3.6             |
| 36        | 43                            | 3.6             |
| 37        | 41                            | 3.6             |
| 38        | 43                            | 3.6             |
| 39        | 41                            | 3.6             |
| 40        | 43                            | 3.6             |
| 41        | 41                            | 3.6             |
|           | March                         | April           |
| 1         | 43                            | 4.5             |
| 2         | 41                            | 4.5             |
| 3         | 55                            | 4.5             |
| 4         | 45                            | 4.5             |
| 5         | 55                            | 4.5             |
| 6         | 57                            | 4.5             |
| 7         | 57                            | 4.5             |
| 8         | 48                            | 4.5             |
| 9         | 45                            | 4.5             |
| 10        | 40                            | 4.5             |
| 11        | 42                            | 4.5             |
| 12        | 43                            | 4.5             |
| 13        | 43                            | 4.5             |
| 14        | 42                            | 4.5             |
| 15        | 43                            | 4.5             |
| 16        | 43                            | 4.5             |
| 17        | 43                            | 4.5             |
| 18        | 43                            | 4.5             |
| 19        | 43                            | 4.5             |
| 20        | 43                            | 4.5             |
| 21        | 43                            | 4.5             |
| 22        | 43                            | 4.5             |
| 23        | 43                            | 4.5             |
| 24        | 43                            | 4.5             |
| 25        | 43                            | 4.5             |
| 26        | 43                            | 4.5             |
| 27        | 43                            | 4.5             |
| 28        | 43                            | 4.5             |
| 29        | 43                            | 4.5             |
| 30        | 43                            | 4.5             |
| 31        | 43                            | 4.5             |
| 32        | 43                            | 4.5             |
| 33        | 43                            | 4.5             |
| 34        | 43                            | 4.5             |
| 35        | 43                            | 4.5             |
| 36        | 43                            | 4.5             |
| 37        | 43                            | 4.5             |
| 38        | 43                            | 4.5             |
| 39        | 43                            | 4.5             |
| 40        | 43                            | 4.5             |
| 41        | 43                            | 4.5             |
Soil cores were divided in the field into 0–15 and 15–30 cm (measuring from the base of the core). One of the five sampling plots was randomly selected and three 1-m cores were taken, except for site 38. Due to the high stones content at site 38, it was possible to sample just two 1-m cores. On return to the laboratory, the 1-m cores were divided into four sections: 0–15, 0–30, 30–50 and 50–100 cm. The rationale behind the sampling approach for the 1-m soil cores was largely based on feasibility and practicality.

Fig. 1 Correlation between measured and modelled SOC at the reference sites at 0–30 cm soil depth. Error bars represent 95% confidence interval of measured values. SOC, soil organic carbon.

Fig. 2 Comparison between modelled and measured SOC at the Miscanthus sites at 0–30 cm soil depth. Error bars represent 95% confidence interval of measured values. SOC, soil organic carbon.
Air-dried soil samples were sieved to 2 mm, and the mass and volume of stones and roots remaining on the sieve were recorded. A subsample of the sieved soil was oven-dried (105 °C for 12 h) and subsequently ball-milled (Fritsch Planetary Mill); samples were analysed for %C using a LECO TruSpect CN analyser (Leco, TruSpec CN, St. Joseph, MI, USA), and a 100 mg subsample was used for the assessment of OC concentration using an elemental analyser (Leco, TruSpec CN). Prior to OC analysis, soil subsamples that were either from sites located on soil types known to contain inorganic C or which had pH values >6.5 were tested for the presence of inorganic C. Samples that tested positive were treated to remove inorganic C by acid fumigation following the procedure detailed by Harris et al. (2001).

The change in SOC was assumed to be the difference between the bioenergy and non-bioenergy pair. Measurements of SOC, soil bulk density, soil texture and soil pH, as well as information on the land-use history, were collated for each field. Soil texture was determined for the top 30 cm soil depth; therefore, soil texture data for the 30–100 cm soil depth were extracted from soil data at 1 km resolution for England and Wales, Scotland and Northern Ireland as described in Bradley et al. (2005), first used to run RothC in support of the Land use, land-use change and forestry (LULUCF) inventory (Falloon et al., 2006).

Air temperature and precipitation data at each location were extracted from the E-OBS gridded data set from the EU-FP6 project ENSEMBLES, provided by the ECA&D project (Haylock et al., 2008), publicly available at http://eca.knmi.nl/. For each location, monthly air temperature and precipitation for each simulated year was collated and a long-term (30 years before transition) average was also calculated (Table 2). Monthly PET was estimated using the Thornthwaite method (Thornthwaite, 1948).
1948), which has been used in other modelling studies when direct observational data have not been available (e.g. Smith et al., 2005; Yokozawa et al., 2010; Bell et al., 2012).

**Model evaluation**

At each site, each transition from conventional (arable or grassland) to bioenergy crop (Miscanthus or SRC-willow) was modelled and the simulated SOC was compared to the measured SOC. Based on the site information provided, the measured SOC at each reference arable/grassland site was used as the starting C input to the model, assuming that the soil at the reference site had been in equilibrium before the transition. The model has not been recalibrated or reparameterized using the data presented in this study; therefore, the presented results are an independent test of the ability of the model to simulate SOC under Miscanthus and SRC-willow as well as change in SOC from grassland/arable.

Fig. 4 Comparison between modelled and measured SOC at the Miscanthus sites at 0–100 cm soil depth. Error bars represent 95% confidence interval of measured values. SOC, soil organic carbon.

Fig. 5 Comparison between modelled and measured SOC at the SRC-willow sites at 0–100 cm soil depth. Error bars represent 95% confidence interval of measured values. SOC, soil organic carbon; SRC, short rotation coppice.
The model was evaluated using input data of measured SOC at the start of the simulation, bulk density and soil texture. Simulations were carried out for 0–30 and 0–100 cm soil depths.

A quantitative statistical analysis was undertaken to determine the coincidence and association between measured and modelled values, following the methods described in Smith et al. (1997) and in Smith & Smith (2007). The statistical significance of the difference between model outputs and experimental observations can be quantified if the standard error of the measured values is known (Hastings et al., 2010). The standard errors (data not shown) and 95% confidence intervals around the mean measurements were calculated for all field sites.

The degree of association between modelled and measured values was determined using the lack of fit statistic (LOFIT) and its significance was assessed using an F-test (Whitmore, 1991) indicating whether the difference in the paired values of the two data sets is significant. All statistical results were considered to be statistically significant at $P < 0.05$.

### Results

The model simulations of the SOC show a good fit against the measured SOC, for both reference (Fig. 1) and bioenergy crops (Miscanthus and SRC-willow), at 0–30 cm soil depth (Figs 2 and 3, respectively).

All the reference sites have been simulated for a time period of ≥30 years without any land-use change and using the field measurements as inputs to the model. Based on the site histories, we assumed that all the reference sites were in equilibrium at the time of sampling. The $r$ value (1) of the reference sites at 0–30 cm soil depth showed a significant ($P < 0.05$) association between modelled and measured values, as well as no significant model bias ($E < E_{95}$) (Table 3).

The correlations between modelled and measured SOC at the Miscanthus and SRC-willow fields, at
0–30 cm soil depth, are presented in Figs 2 and 3, respectively. Overall, the simulated C correlates well with the measured SOC (Table 3).

The $r$ value of the SOC at both Miscanthus ($r = 0.95$) and SRC-willow ($r = 0.72$) sites showed a significant ($P < 0.05$) association between simulated and measured values. The calculated value of $E$ indicated that the simulations at both Miscanthus and SRC-willow sites show no significant bias ($E < E_{95}$). Finally, the LOFIT value showed that the model error was within (i.e. not significantly larger than) the measurement error.

At most of the Miscanthus sites, the simulated SOC was within the 95% confidence interval of the measured SOC (error bars in Fig. 2). At sites 11, 16 and 19, the model estimated a lower SOC compared to the measured values (51.9 vs. 54.6 t C ha$^{-1}$, 56.4 vs. 63.6 t C ha$^{-1}$, 55.2 vs. 58.9 t C ha$^{-1}$, respectively).

The simulated SOC at the SRC-willow sites was within the 95% confidence interval of the measured SOC (error bars in Fig. 3). The only exceptions were found at sites 4 and 33 where the model estimated a lower SOC compared to the measured values (60.0 vs. 65.7 t C ha$^{-1}$, 94.3 vs. 107.4 t C ha$^{-1}$, respectively) while for sites 8 and 20 the model simulated a higher accumulation of SOC compared to the site measurements. However, simulated SOC showed a good fit against soil measurements at all sites (Table 3).

The model simulations of the total C at 0–100 cm soil depth again showed a good correlation with the measured SOC, for both Miscanthus (Fig. 4) and SRC-willow fields (Fig. 5). High variation of the measured SOC was found at certain Miscanthus (site 30 and site 38) and SRC-willow (site 18 and site 33) sites. The statistics of the SOC at the 0–100 cm soil depth reflected the good model performance found for the top soil layer, with a high correlation between simulated and measured values and no significant bias for both Miscanthus and SRC-willow sites (Table 3).

The change in SOC ($\Delta$SOC) has been calculated as the difference between the SOC at the bioenergy sites and the SOC at the reference. These results are important as they directly show the effect of the land-use transition itself, that is the long-term accumulation or loss of SOC due to the transition occurring. At 0–30 cm soil depth, the modelled transitions from conventional crops (arable and grassland) to Miscanthus and SRC-willow lead to a $\Delta$SOC that was within the 95% confidence intervals of the measured values (Figs 6 and 7).
Overall, at 0–100 cm, the ΔSOC simulated by the model followed the same direction of the measured SOC changes, for both transitions to Miscanthus (Fig. 8) and SRC-willow (Fig. 9). All the ΔSOC simulated by the model is within the 95% confidence intervals of the measured values. The simulated changes in SOC are well associated with the measured values, with a r value for Miscanthus of 0.98 and 0.97 at 0–30 and 0–100 cm soil depth, respectively, and for SRC-willow of 0.98 and 0.84 at 0–30 and 0–100 cm soil depth, respectively. Furthermore, the statistical analysis on the ΔSOC showed no model bias (E < E95) and a good coincidence [F < F (critical at 5%)] between modelled and measured changes in SOC after transition to Miscanthus and to SRC-willow (Table 4).

Discussions

The present study emphasizes the high accuracy of the ECOSSE model to simulate SOC and SOC changes after transitions to SRC-willow and Miscanthus crops in the United Kingdom. The statistical analysis of the SOC and SOC changes at both 0–30 and 0–100 cm soil depths highlights the absence of significant error between simulated and measured values as well as the absence of significant bias in the model. As for the bioenergy plantations, SOC in the reference fields has been accurately simulated by the model. The extremely high correlation for the reference fields shows a good performance of the model spin-up, which is used by the model to reach a state of equilibrium under the specified inputs. However, it is important to stress that it does not confirm that the reference sites are in an equilibrium condition. In fact, at certain bioenergy sites, the model under/overestimated the SOC at 0–30 cm soil depth. A possible explanation of such model underestimates could be that the soil at the reference sites, all arable cultivations established before 1990, were not in equilibrium at the time of the transitions. The initialization of the model is based on the assumption that the soil column is at a stable equilibrium under the initial land use at the start of the simulation (T0); therefore, the SOC measured at the reference site at the time of sampling (T1) is assumed to be at the same level as at the time of the transition to the new crop. The equilibrium level depends on several factors: the input of organic material and its rate of decomposition, the rate at which existing SOM is mineralized, soil texture and climate.
The time to reach such equilibrium between vegetation and soil system is extremely unpredictable as all the factors involved in the stabilization process are in constant interaction with each other (Jenkinson, 1990).

Another source of discrepancy between modelled and measured SOC could also be attributed to the divergence between model estimates of the plant inputs to the soil and the actual field value. In the ECOSSE model, the SI is estimated by a modification of the Miami model (Lieth, 1972), which is a simple conceptual model that links the NPP to annual mean temperature and total precipitation (Grieser et al., 2006). The NPP is rescaled for each land-cover type, and SI is then estimated as a fixed proportion of the NPP according to the land cover. The rescaling factors for Miscanthus and SRC-willow have been derived from comparison of unadjusted Miami results with published yield data for Miscanthus in the United Kingdom (Hastings et al., 2013) and SRC-willow (Styles et al., 2008). The Styles et al. (2008) publication reports an expected annual yield of 9 t DM ha⁻¹ yr⁻¹ for SRC-willow in Ireland; this figure is comparable with UK estimates reported by Tallis et al. (2013) (9.0 t DM ha⁻¹ yr⁻¹) and Hastings et al. (2014) (6.1–12.1 t DM ha⁻¹ yr⁻¹). The application of the

![Figure 9](image.png)

**Fig. 9** Measured and modelled change in SOC after transition to SRC-willow at 0–100 cm soil depth. Error bars represent 95% confidence interval of measured values. Solid line represents 1:1 correlation between measured and modelled values. SOC, soil organic carbon; SRC, short rotation coppice.

|          | 0–30 cm depth | 0–100 cm depth |
|----------|---------------|---------------|
|          | Miscanthus    | SRC-willow    | Miscanthus    | SRC-willow    |
| **r**    | 0.98          | 0.98          | 0.97          | 0.84          |
| **t-value** | 21.59        | 20.92        | 16.99        | 6.52          |
| **t-value at (P = 0.05)** | 2.10        | 2.10        | 2.1          | 2.1           |
| **E**     | −34           | 47.51        | 114          | −134          |
| **E₉₅ (95% Confidence limit)** | −253        | 657.24       | 657          | −962          |
| **F**     | 0.02          | 0.03          | 0.04         | 0.2           |
| **F (Critical at 5%)** | 1.69        | 1.69        | 1.69          | 1.7           |
| **Number of values** | 20            | 20            | 20           | 18           |

Table 4 ECOSSE model performance at simulating soil C changes (ΔC) at the Miscanthus and SRC-willow fields for two soil depths (0–30 cm and 0–100 cm). Association is significant for **t > t** at (P = 0.05). Model bias is not significant for **E < E₉₅**. Error between measured and modelled values is not significant for **F < F** (critical at 5%).

SRC, short rotation coppice.
rescaling factors has been necessary as the Miami model has been developed to estimate NPP at a global scale and based on environmental variables only, while land-cover type is a key aspect in the ECOSSE model. In the present study, this approach has provided good plant input predictions, and consequently SOC figures, at 17 Miscanthus and 16 SRC-willow sites in the United Kingdom; it has also been previously applied with good results on the prediction of SOC in 29 transitions to SRF (Dondini et al., 2015). However, localized weather conditions at some sites may cause divergent yields compared to that predicted by the Miami model. A study by Hastings et al. (2014) reported estimated yield potential for current and future climates across Great Britain; Miscanthus yield, estimated using the Miscanfor model, ranged from 7.4 to 13.1 t DM ha\(^{-1}\) yr\(^{-1}\) across regions in Great Britain, whereas estimates of willow yield (from the ForestGrowth-SRC model) ranged from 6.1 to 12.1 t DM ha\(^{-1}\) yr\(^{-1}\) under current climate.

High variability in the measured SOC at 1 m depth was found at the Miscanthus site 38 (error bars in Fig. 4). The high variability in SOC at this site is mainly due to the higher stone content in the soil cores compared to the other Miscanthus fields and to a lower number of soil cores collected at this site. In fact, due to the high stone content, two soil cores (instead of three) have been collected at site 38, leading to a bigger 95% confidence interval of the measured values compared to other sites. A high error in the measured SOC has also been found at site 30 and at two SRC-willow sites (sites 18 and 33).

Many factors influence SOC, including temperature, precipitation, NPP and soil physical characteristics (Parton et al., 1987), all of which are spatially variable. The result is substantial variability in SOC, with coefficients of variation as high as 20% even in a visually uniform cultivated field (Robertson et al., 1997). As variability increases, the minimum number of samples needed to detect a given level of change increases. Furthermore, short-term changes in SOC are usually small relative to the amount of C in soil (Conant & Paustian, 2002). Therefore, all transition units reported in the current study were sampled using a hierarchical design, developed to capture variability across different spatial scales (Conant & Paustian, 2002; Conant et al., 2003), especially for the top 30 cm soil.

The results of the present work revealed a strong correlation between modelled and measured SOC and SOC changes to Miscanthus and SRC-willow plantations, at two soil depths (Tables 3 and 4). Previous studies on ECOSSE have used large spatial data sets (Smith et al., 2010a,b) to evaluate the model accuracy to simulate SOC. Smith et al. (2010a) presented an evaluation of the ECOSSE model to simulate SOC at a national scale, using data from the National Soil Inventory of Scotland. This data set provided measurements of SOC and SOC change for the range of soils, climates and land-use types found across Scotland. The results of the present work are in agreement with the publication of Smith et al. (2010a), which reported a high degree of association of the ECOSSE modelled values with the measurements in both total C and change in C content in the soil.

The performance of the ECOSSE model in simulating SOC and SOC changes was recently evaluated for SRF plantations in the United Kingdom (Dondini et al., 2015). The same approach has been used in the present study to test its application for transitions to Miscanthus and SRC-willow in the United Kingdom. The statistical analysis of the results presented here is in accordance with the results presented by Dondini et al. (2015) for SRF, revealing no significant error between modelled and measured SOC and SOC changes, as well as no significant model bias. The latter is a promising result, given that this work is an independent evaluation of ECOSSE, and therefore, the model had not been further improved or parameterized to produce the outputs under Miscanthus and SRC-willow plantations.

This work reinforces previous studies on the ability of ECOSSE to simulate SOC and SOC changes at field level and using limited data to initialize the model. The high degrees of association with measured SOC under Miscanthus, SRC-willow and SRF (Dondini et al., 2015) plantations in the United Kingdom allow confidence in using this process-based model for quantitatively predicting the impacts of future land use on SOC, at site level as well as at national level.

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