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ELUM: A spatial modelling tool to predict soil greenhouse gas changes from land conversion to bioenergy in the UK

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ABSTRACT

The ELUM Software Package spatially predicts the net soil greenhouse gas balance of land-use change to grow energy crops in the UK up to 2050. It is able to support a range of analyses of bioenergy, and was developed in consultation with anticipated users. Results can be obtained according to specific interests, viewed in the graphical interface and exported for a variety of purposes. The functionality of the software is demonstrated through different case studies, which show an array of applications.

Software availability

Name of software: ELUM Software Package
Developer: Mark Pogson, University of Aberdeen, University of Bolton and Liverpool John Moores University
Availability and documentation: Software and user guide freely available via http://www.elum.ac.uk/
Year first available: 2016
Software required: Java, Microsoft Windows 32-bit or higher
Programming languages: Java, Python, Fortran

1. Introduction

Bioenergy is predicted to contribute 10% of primary energy demand in the UK by 2050, rising from 3% currently (DECC, 2012). Up to 3Mha of the 18Mha of agricultural land in the UK may be dedicated to biomass feedstock production (UK Bioenergy Strategy, 2012; Rowe et al., 2009; Taylor, 2008), with comparable predictions elsewhere (Mantau et al., 2010; U.S. DOE, 2006).

Bioenergy has the potential for favourable greenhouse gas (GHG) balances (Smith et al., 2015; Bringezu et al., 2009), but this depends on the effects of land-use change (LUC) to grow energy crops (Berndes et al., 2011; Guo and Gifford, 2002). The Ecosystem Land Use Modelling & Soil Carbon GHG Flux Trial (ELUM) project has quantified the GHG balance of LUC to grow energy crops in the UK through a combination of field measurements and simulation (Harris et al., 2014). As part of this, the ECOSSE model (Smith et al., 2010) has been successfully evaluated to predict soil GHG balances at site-level (Dondini et al., 2014, 2015), and applied spatially to estimate the potential effects of large-scale energy crop cultivation in the UK (Richards et al., 2016).

There is an established need for spatial modelling of a range of aspects of LUC (Celio et al., 2014; Mas et al., 2014) and user-friendly interfaces for environmental modelling software (Schiavina et al., 2015). Due to the predicted scope of bioenergy deployment in the UK, it is important that estimates of its impacts are available to a wide audience – especially scientists and policy makers in public and private sectors – and that users can obtain results specific to their interests rather than rely on published data for particular scenarios. Existing software is not suitable for this purpose for

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several reasons, including large computing requirements and highly involved operation, which may require extensive data processing and knowledge of programming code. Here we present the ELUM Software Package, an accessible spatial modelling tool which provides estimates of the net soil GHG balance of LUC to grow energy crops anywhere in the UK up to 2050 according to a range of options. The software is intended to support bioenergy value chain and life-cycle assessments of the likely consequences of different bioenergy land-use policies and practices, and was developed in consultation with anticipated users to ensure its suitability.

For clarity and simplicity, rather than presenting absolute emissions, results represent the difference between emissions following LUC and corresponding emissions had no transition occurred; results therefore show the effect of the LUC itself. Results are reported as CO_2-equivalent (CO_2e) values for net GHG, CO_2, N_2O and CH_4 emissions, and changes in soil carbon (soil C), per hectare of land and per oven-dry tonne of biomass yield.

Carbon stored in the harvested biomass is excluded from results in order to separate out the effects of LUC on the soil itself, as are all associated cultivation and harvesting emissions, such as from fertiliser production, machinery and transport. This enables results to be used for a range of purposes without imposing undue assumptions. Only direct transitions from existing land-uses are considered; indirect LUC and future transitions (Searchinger et al., 2008) are beyond the scope of ELUM.

ELUM considers LUC to grow the following first-generation crops (Kretschmer, 2011): wheat, sugar beet and oil seed rape (OSR), and the following second-generation crops (Rowe et al., 2009): short rotation forestry (SRF) Poplar, short rotation coppice (SRC) Willow, and *Miscanthus* × *giganteus* (*Miscanthus*). Conversion of land is considered from arable, grass and forest.

We describe the development and functionality of the software package before demonstrating its use in different case studies. These highlight important points to consider when interpreting results, and also show potential opportunities and risks associated with LUC to grow energy crops. However, the case studies are neither predictions of likely bioenergy deployment, nor recommendations of policies to pursue or avoid.

2. The ELUM software package

2.1. Development

The ELUM Software Package is intended to be accessible to a wide range of users. The following key requirements were therefore identified from the outset, and refined throughout the development process in response to user feedback:

- Accessible: free to use, graphical user interface (GUI), low computing requirements, no installation, flexible data storage options;
- Standalone: no separate data or software requirements (except Java running on Windows), results and analysis are presented within package, comprehensive user guide;
- Immediate: results are obtained quickly and directly, default options are provided;
- Flexible: various options are provided for results, regions and data export.

Many features benefit all users, such as speed and ease of use, but others involve balancing conflicting requirements, such as the need for flexible options versus the potential for confusion and misinterpretation. These issues were resolved in a number of ways, including the provision of appropriate default options, pop-up information windows, and colour-coding and labelling of results.

Software development included extensive interaction with anticipated users, ranging from informal discussions throughout the three-year project, to an annual review process with feedback from an academic and industrial panel. This motivated several features, including options for regional selection, types of results, analysis tools and data formats (Hillier et al., 2016). It also helped in creating a help file suitable for a broad audience, which documents not only the software but also the model, results and terminology. Initial users include the Bioenergy Value Chain Model (Samsatli et al., 2015), for which the ability to export results in different formats and disaggregate emissions is particularly important.

2.2. Structure

The ELUM Software Package comprises two main sections: a GUI (Fig. 1), and a collection of programs and data files (Fig. 2), which are all operated from the GUI. ELUM is supplied as a stand-alone folder which does not require installation.

2.3. Underlying model

The ECOSSE model (Smith et al., 2010) underlies results in ELUM. It is not part of the software itself but has been used to obtain the results, which are stored in a look-up table (Fig. 2).

ECOSSE models soil disturbance (due to planting, harvesting or removal of crops), changes in soil carbon inputs from litter biomass (via decomposition rates), and changes in fertiliser quantity and timing. Please see Richards et al. (2016) for a full description of the ECOSSE simulations performed for ELUM, including data inputs (EUROSTAT, 2014; FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012), processing (Hastings et al., 2014; Pyatt et al., 2001; Thompson and Matthews, 1989; Lieth, 1975) and calculation of CO_2-equivalent (CO_2e) emissions (IPCC, 2001, 2013).

2.4. Meta-model

The meta-model is a program in the software package which accesses results from the look-up table and processes them according to user selections. The meta-model, in combination with the look-up table, is used in place of the underlying ECOSSE model to simplify operation and significantly decrease computation time.

In order to reduce the size of the look-up table, only results for default fertiliser and yield values are stored; results for a range of non-default values are estimated in the meta-model by rescaling results according to relationships obtained from linear-regression of ECOSSE results. These relationships provide very good approximations to the actual ECOSSE outputs, as described further in the user guide.

Users can select geographical areas by grid reference or by regions from a range of administrative levels. Results have a spatial resolution of 1km but are best used at regional and national scales due to inherent spatial uncertainties in the underlying data.

Two different spatial masks can be applied by the meta-model. UK land-cover data are obtained from CEH Land Cover Map 2007 (Morton et al., 2011), which rescale results according to the initial land-cover in each grid cell. By applying the land-cover mask, spatial per-hectare results show the combination of emissions and available land (i.e. the effective emissions per hectare spread across each whole grid cell); thus summed time-series results reflect the total available land for the initial land-use of each transition. By removing the land-cover mask, results represent emissions on productive land without accounting for how much land is available; this allows users to separate out the effects of LUC and land availability, or post-process results to apply different land-cover masks. In contrast, land constraints data are obtained from Lovett et al. (2014), which are used to exclude entire grid cells deemed